# NAVAL POSTGRADUATE SCHOOL

**MONTEREY, CALIFORNIA**

# THESIS

**UNDERSTANDING AND PREDICTING URBAN PROPAGATION LOSSES**

by

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September 2009

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| REPORT DOCUMENTATION PAGE | | | *Form Approved OMB No. 0704-0188* |
|---|---|---|---|
| Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503. | | | |
| **1. AGENCY USE ONLY *(Leave blank)*** | **2. REPORT DATE** September 2009 | **3. REPORT TYPE AND DATES COVERED** Master's Thesis | |
| **4. TITLE AND SUBTITLE** Understanding and Predicting Urban Propagation Losses | | | **5. FUNDING NUMBERS** |
| **6. AUTHOR(S)** LCDR Mark R. Alexander, USN | | | |
| **7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)** Naval Postgraduate School Monterey, CA 93943-5000 | | | **8. PERFORMING ORGANIZATION REPORT NUMBER** |
| **9. SPONSORING /MONITORING AGENCY NAME(S) AND ADDRESS(ES)** N/A | | | **10. SPONSORING/MONITORING AGENCY REPORT NUMBER** |
| **11. SUPPLEMENTARY NOTES** The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government. | | | |
| **12a. DISTRIBUTION / AVAILABILITY STATEMENT** Approved for public release; distribution is unlimited | | | **12b. DISTRIBUTION CODE** A |


**13. ABSTRACT (maximum 200 words)**

Modern day warfare has presented the United States with a more technically savvy opponent in conflicts that have moved away from the traditional battlefield to the populated environment of the big city. Battle space dominance no longer refers simply to the physical nature of war, but now also encompasses a digital environment with a greater influence on Information Warfare. One of the keys to successfully maintaining open wireless lines of communication and extracting data, or denying the adversary the ability to communicate, is a complete understanding of radio wave propagation and the positive and negative effects of spreading and propagation losses. In a communication link, or radio wave transmission, several sources of degradation are mathematically accounted for, to include losses due to materials used, equipment setup, environmental factors, and interference associated with the actual frequencies. Up until recently, there were no studies evaluating the potential multipath losses that exist between a transmitter and receiver in an urban environment. This thesis will examine existing urban propagation models and evaluate their effectiveness in a variety of urban environments through a range of frequencies.


| **14. SUBJECT TERMS** | | | **15. NUMBER OF PAGES** |
|---|---|---|---|
| Radio Wave Propagation, Urban Propagation Loss, Okumura, Hata, Friis, Propagation Loss Model, Propagation Loss Calculator, Free Space Path Loss | | | 105 |
| | | | **16. PRICE CODE** |
| **17. SECURITY CLASSIFICATION OF REPORT** | **18. SECURITY CLASSIFICATION OF THIS PAGE** | **19. SECURITY CLASSIFICATION OF ABSTRACT** | **20. LIMITATION OF ABSTRACT** |
| Unclassified | Unclassified | Unclassified | UU |

NSN 7540-01-280-5500 Standard Form 298 (Rev. 2-89) Prescribed by ANSI Std. 239-18

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# UNDERSTANDING AND PREDICTING URBAN PROPAGATION LOSSES

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Submitted in partial fulfillment of the
requirements for the degree of

**MASTER OF SCIENCE IN INFORMATION WARFARE SYSTEMS ENGINEERING**

from the

**NAVAL POSTGRADUATE SCHOOL**
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# ABSTRACT

Modern day warfare has presented the United States with a more technically savvy opponent in conflicts that have moved away from the traditional battlefield to the populated environment of the big city. Battle space dominance no longer refers simply to the physical nature of war, but now also encompasses a digital environment with a greater influence on Information Warfare. One of the keys to successfully maintaining open wireless lines of communication and extracting data, or denying the adversary the ability to communicate, is a complete understanding of radio wave propagation and the positive and negative effects of spreading and propagation losses. In a communication link, or radio wave transmission, several sources of degradation are mathematically accounted for, to include losses due to materials used, equipment setup, environmental factors, and interference associated with the actual frequencies. Up until recently, there were no studies evaluating the potential multipath losses that exist between a transmitter and receiver in an urban environment. This thesis will examine existing urban propagation models and evaluate their effectiveness in a variety of urban environments through a range of frequencies.

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# I. INTRODUCTION

## A. FORWARD

Modern day warfare has presented the United States with a more technically savvy opponent in conflicts that have moved away from the traditional open-space battlefields to the populated environment of the big city. Battlespace dominance no longer refers simply to the physical nature of war, but now also encompasses a digital environment with a greater influence on Information Warfare. One of the keys to successfully maintaining open wireless lines of communication and extracting data, or denying the adversary the ability to communicate, is a complete understanding of radio wave propagation and the positive and negative effects a propagated signal will experience due to spreading, interference and propagation losses. In a communication link, or radio wave transmission, several sources of degradation are mathematically accounted for when characterizing the communication channel, to include losses due to materials used, equipment setup, environmental factors, and interference associated with the actual frequencies that are in use within the managed spectrum. Up until recently, there were few studies evaluating the potential multipath losses that exist between a communication system transmitter and receiver in an urban environment.

Due to the recent interest in propagated signals, models have been developed and currently exist that predict path losses associated with the urban environment, but the

accuracy of each model generally exists only in a small window of specific parameters that are involved. In this project, a spreadsheet with user-defined parameters will be developed utilizing existing urban radio wave propagation models. The development of this spreadsheet tool has two principle objectives: 1) To organize existing models in such a way that each model can be easily associated with its ideal urban conditions and, at the same time, giving an indication of the best model available for various urban environments. 2) The second objective is to develop the spreadsheet into a simple operational tool that allows users to input their existing urban conditions and the tool developed by this effort then provides the user an indication of the best suited urban propagation loss model along with a characterization of the associated losses expected to be involved.

## B. PURPOSE

This study evaluates existing models in an attempt to identify the most accurate radio wave propagation losses in any given specific environment and develops a basic tool that allows users to determine the associated loss based on their input parameters. Beyond basic algorithms calculating an expected propagation loss, the study and comparative tool will demonstrate the variation in responses expected across the body of available computational models, along with help in evaluating the impact of altering the parameters within a specific model that are actually user-adjustable in an operational environment.

## C. THESIS RELEVANCE

As the nature of modern day warfare illuminates the importance of Information Operations, understanding and implementing measures to ensure uninterrupted communications have become even more crucial. Long gone are the days of basic open line-of-sight battlefield communications. With so many of today’s conflicts geared towards insurgency types of warfare embedded in urban environments, the requirement exists to establish reliable and robust communication networks capable of overcoming the additional constraints that exist in and around the physical structures of a city. In urban conflict, operational units cannot always rely on, or trust, the communication infrastructure that exists in the adversarial state or urban battlefield. To establish an autonomous wireless communication network, operators must understand the impact of their surroundings on the signals they are transmitting. This study will help define the urban wireless environment and the expected losses in a variety of urban scenarios.

## D. THESIS METHODOLOGY/RESEARCH OVERVIEW

A literature review revealed the existence of several models designed to predict the radio wave propagation losses in an urban environment, of which the Hata Model appeared to be the most widely accepted for a general set of environmental parameters. Several of the models either incorporate, or are based on the Hata Model, with more restricted parameters. In many cases, the losses encountered in the urban environment are actually twice as large as those encountered in unobstructed line-of-sight

(free space) communications. Most of the existing urban models are empirical in nature based only on mathematical curves derived to fit actual urban radio transmission data sets collected in the late 1960s. Most sources of urban propagation loss literature were published more than 10 years ago, indicating that there has not been much recent development in being able to reliably predict urban transmission losses from first principles without actually testing the signals in the given environment.

From an operator's perspective, it was difficult to find one source that indicated a best general fit model for a given urban environment providing a wide variety of capability with specific transmission parameters. Each model has an associated set of recognized parameter limitations, but those ranges often varied depending on the source. Expensive software packages are available that appear to calculate transmission losses based on a particular model and then attempt to extend the coverage of the given scenario, but most of these commercial tools require an in-depth knowledge of the actual urban conditions.

Based on the literature review, a true need exists for a simple tool that takes operator input of urban environmental and transmission parameters, and determines the best fit propagation loss model, calculates the associated loss for the model and parameters of interest, demonstrates the variation in the calculated losses over several models, and most importantly, provides user guidance on the impact of adjusting transmission parameters that might be under user control.

## E. THESIS ORGANIZATION

Chapter II discusses the basics of radio wave propagation and explains several of the loss factors that occur in the urban environment which are not present in basic open air radio wave transmissions. A history of urban propagation models is provided, along with a description of each of the models being used in this study. Benefits and shortfalls of each model are discussed.

Chapter III provides an in-depth overview of the development of the Microsoft Excel urban propagation loss tool for this research, to include the four major output sections: determination of the best fit model, calculation of propagation loss, demonstration of the variation of losses associated with selected models, and the impact of adjusting transmission parameters. A users guide (Appendix A) providing direction on how to use the propagation loss tool is also discussed in this chapter.

Chapter IV addresses the results and performance analysis using the propagation loss tool developed. Test parameters are developed and discussed, demonstrating the utility of the tool. Collected data is analyzed to determine best fit models for particular urban environment categories. Calculated propagation losses are compared to free space losses and explanations of variation are discussed.

Chapter V provides an overall conclusion of the utility of the Microsoft Excel urban propagation loss tool. The advantages of using specific models to predict losses in certain situations is provided along with descriptions of the overall impact of altering adjustable parameters to

reduce propagation losses. This chapter also provides recommendations for potential future research of radio propagation losses in the urban environment, to include recommendations for further developments to the Microsoft Excel propagation loss tool developed in this study.

# II. BACKGROUND

## A. HISTORY

Long-range communications have existed for hundreds of years, extending back to the use of smoke signals, drum beats, horns, and light signals. The process of transmitting and receiving intelligence was significantly improved with the introduction of the telegraph and telephone, essentially extending the communications link around the world, between any two points that could be connected by wire.

In 1865, James Clerk Maxwell predicted that electromagnetic waves could be transmitted through space at the speed of light, which was the basis for radio wave communications. In the late 1800s, Heinrich Hertz experimented with Maxwell's predictions and revealed that electromagnetic waves were actually both producible and detectable. Guglielmo Marconi continued this development, and by 1895, had developed a radio-telegraph system that he first used in 1901 to transmit a transatlantic signal. Initial radio communications used low and medium frequencies, but the need for higher frequencies existed to cover longer ranges.

Since World War II, military units have been working with high frequency (HF), very high frequency (VHF), and ultrahigh frequency (UHF) radios. Since the 1960s, studies have continued to evaluate radio wave propagation and the associated losses. With the development of high frequency

mobile communications systems, it has become necessary to better understand the transmission of radio frequencies up around 3,000 megahertz (MHz).[1]

## B. RADIO WAVE TRANSMISSION BASICS

Many factors contribute to the attenuation of a radio wave as it propagates through a particular environment. In an effort to limit the scope of this study, below is list of some, not all, of the contributing factors, with a brief description of each.

### 1. Free Space Loss

Free space loss describes the loss that occurs as a signal travels through space with no other attenuation caused by outside influences. This occurs because the signal spreads out as the distance from the transmitter increases.[2]

### 2. Absorption

Absorption is a loss that occurs if the signal passes through varying mediums or obstacles in which some of the transmitted signal is converted into another form of energy, usually thermal, and some of it continues to propagate. Any material or atmospheric condition that is non-transparent to electromagnetic signals will result in absorption of the transmitted signal. The conversion of energy occurs at the

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1 John Pike, “Radio-Communications Theory,” 19 Mar 1999, <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

2 Ian Poole, “Radio Signal Path Loss,” n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

molecular level, resulting from the interaction of the energy of the radio wave and the material of the medium or obstacle.[3]

### 3. Scattering

Scattering is a condition that occurs when a radio wave encounters small disturbances of a medium, which can alter the direction of the signal. Certain weather phenomena such as rain, snow, and hail can cause scattering of a transmitted radio wave. Scattering is difficult to predict because of the random nature of the medium or objects that cause it.[4]

### 4. Reflection

Reflection occurs when a radio wave approaches the boundary of two mediums and redirects back into the original medium in a different direction, rather than permeating through into the new medium.[5]

### 5. Refraction

Refraction occurs when a radio wave passes from one medium to another with different refractive indices resulting in a change of velocity within an electromagnetic wave that results in a change of direction.[6]

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[3] Ian Poole, "Radio Signal Path Loss," n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

[4] Ibid.

[5] Ibid.

[6] Ibid.

### 6. Diffraction

Diffraction losses occur when there is an obstacle in the path of the radio wave transmission and the radio waves either bend around an object or spread as they pass through an opening. Diffraction can cause great levels of attenuation at high frequencies. However, at low frequencies, diffraction actually extends the range of the radio transmission.[7]

### 7. Polarization Fading

Polarization is used in an electromagnetic wave to describe the direction of the electric field vector. Fading is a radio wave's variation in signal strength, caused by a change in the polarization of the transmitted radio wave.[8] Fading can result from reflection, refraction, or absorption. It is a significant problem because antennas are designed to receive a radio wave in a certain polarization, and when the polarization of the signal is changed, the receiving antenna is incapable of receiving the polarization changes.

### 8. Multipath Fading

Multipath fading refers to the fading that occurs as a result of the multiple paths that a signal ends up taking between the transmitter and receiver. Because of the varying arrival times of the signals from the various paths, the signals may or may not be in phase with each other. If

[7] Larry Simmons, *Electronics Technician – Antennas and Wave Propagation* (Pensacola, FL: Naval Education and Training Professional Development and Technology Center, 1995), 1-8.

[8] Ibid., 1-9.

the radio waves are received in phase, they actually combine to form a stronger signal. If the radio waves are out of phase, a weaker signal is produced. Multipath fading is the primary concern in the urban environment.[9]

### 9. Terrain

The terrain over which a signal propagates accounts for a great deal of the loss it experiences along its path. As expected, mountainous terrain can significantly degrade or completely block a signal, but the composition of the terrain can also cause attenuation, especially at low altitudes. Radio waves tend to travel better over more conductive mediums such as water, but encounter more attenuation traveling over areas of dirt or sand.[10]

### 10. Vegetation

Just like the terrain, vegetation can impact the transmission of radio waves. Solid trees can cause significant attenuation, but even leaves can cause scattering of a signal.[11]

### 11. Buildings

Buildings and other man-made structures can cause losses due to all of the above factors, and are by far the main source of attenuation in an urban environment. This

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[9] Larry Simmons, *Electronics Technician – Antennas and Wave Propagation* (Pensacola, FL: Naval Education and Training Professional Development and Technology Center, 1995), 1-8.

[10] Ian Poole, “Radio Signal Path Loss,” n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

[11] Ibid.

study is designed to attempt the difficult task of accurately accounting for the losses caused by these structures.[12]

### 12. Other Losses

There are many other factors that account for radio wave propagation losses, to include the many layers of the atmosphere which have varying effects on signals, depending on the frequency of transmission and the characteristics associated with the atmosphere.

## C. FRIIS TRANSMISSION EQUATION

Harald T. Friis defined the physics of electromagnetic wave behavior in free space with the Friis Transmission Equation (1).

$$\frac{P_r}{P_t} = G_t G_r \left( \frac{\lambda}{4\pi d} \right)^2 \qquad (1)$$ [13]

Where:
$P_r$ = Received Power (Watts)
$P_t$ = Transmitted Power (Watts)
$G_t$ = Gain of transmit antenna
$G_r$ = Gain of receive antenna
$\lambda$ = wavelength (m)
d = distance between transmitter and receiver (m)

[12] Ian Poole, “Radio Signal Path Loss,” n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

[13] Bill Lane, "Topic 17: Propagation Characterization," n.d., <http://www.fcc.gov/pshs/techtopics/techtopics17.html>(31 Aug 2009).

The Friis equation shows that the ratio of the electromagnetic radio wave power received at the receiving antenna to the power transmitted at the transmitting antenna is a function of the transmitting distance, the wavelength of the transmitted frequency, and the gain of each antenna. This equation only deals with electromagnetic properties and no other losses.[14]

When expressed as the ratio of effective isotropic radiated power transmitted to effective isotropic radiated power received, the Friis Transmission Equation (2) represents the Free Space Path Loss (FSPL), accounting for signal losses between a transmitter and receiver in free space with no external influences.

$$FSPL = \frac{EIRP_t}{EIRP_r} = \frac{P_t G_t}{P_r G_r} \qquad (2)$$[15]

Assuming both antennas are isotropic antennas, the transmitter and receiver gain both equal one and equation (2) simplifies to a ratio of powers, essentially removing the gain values from the equation. Using equation (1) and evaluating equation (2) produces the free-space loss expression shown below as equation (3).

$$FSPL = \left( \frac{4\pi d}{\lambda} \right)^2 \qquad (3)$$[16]

[14] *Range Calculation for 300 MHz to 1000 MHz* (Atmel Corporation, 2009), 2.

[15] Bill Lane, "Topic 17: Propagation Characterization," n.d., <http://www.fcc.gov/pshs/techtopics/techtopics17.html>(31 Aug 2009).

Reformatting the wavelength value into frequency and speed of light components as shown in equation (4) allows the constant values to eventually be separated from the adjustable factors, simplifying the equation.

$$FSPL = \left(\frac{4\pi df}{c}\right)^2 \qquad (4)[17]$$

where:

$$\lambda = \frac{c}{f} \qquad (5)$$

c = speed of light = 299,792,458 meters per second

f = transmission frequency

Equations (6) and (7) show the conversion to the decibel form of the Free Space Loss Equation.

$$FSPL\,(dB) = 10\log_{10}\left(\left(\frac{4\pi df}{c}\right)^2\right) \qquad (6)[18]$$

$$FSPL\,(dB) = 20\log_{10}\left(\frac{4\pi df}{c}\right) \qquad (7)[19]$$

Equation (8) converts the FSPL (dB) equation to an addition problem, separating the constants from the

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[16] Bill Lane, "Topic 17: Propagation Characterization," n.d., <http://www.fcc.gov/pshs/techtopics/techtopics17.html>(31 Aug 2009).

[17] Ibid.

[18] Ibid.

[19] Ibid.

adjustable factors, resulting in the simplified equation (9) used later in this study as the Free Space Path Loss equation. As shown, equation (9) requires that distance (d) be expressed in kilometers and that frequency (f) be expressed in MHz.

$$\text{FSPL (dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 20\log_{10}\left(\frac{4\pi}{c}\right) \quad (8)$$ [20]

$$\text{FSPL (dB)} = 20\log_{10}(d) + 20\log_{10}(f) + 32.44 \quad (9)$$ [21]

The remaining quantity used in the Friis transmission equation is the antenna gain for the transmit and receive antennas. The gain of any antenna can be expressed as follows:

$$G = \frac{4\pi A_{eff}}{\lambda^2} = \frac{4\pi \varepsilon A_p}{\lambda^2} \quad (10)$$ [22]

Where:
$A_{eff}$ = antenna effective area
$A_p$ = antenna physical area (for example $\pi r^2$ for a dish antenna)
$\varepsilon$ = antenna aperture efficiency ($0 < \varepsilon < 1$)

The gain of an antenna can also be expressed in sum format using decibels as follows:

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[20] Bill Lane, "Topic 17: Propagation Characterization," n.d., <http://www.fcc.gov/pshs/techtopics/techtopics17.html>(31 Aug 2009).

[21] Ian Poole, “Radio Signal Path Loss,” n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

$$G = -42.2 + 20\log_{10}(f) + 20\log_{10}(D)$$

(11)[23]

Where:
A typical antenna efficiency of 55% (0.55) has been assumed
f = the center frequency in MHz of the transmit signal
D = antenna diameter (meters)

## D. RADIO WAVE PROPAGATION MODELS

A radio wave propagation model is a series of mathematical calculations derived to predict a signal’s path of transmission and the associated losses in a given environment, based on varying parameters such as frequency, distance, and the obstacles in the path of transmission. The propagation models are empirical in nature, with formulas derived from actual data sets. The collected data is analyzed and formulas are developed to fit the data curves. These formulas may only provide an accurate fit over a certain range of the collected data, resulting in limitations on the parameter ranges that restrict accurate predictions to portions of the overall range at possible values. The models are developed to help predict path characteristics and losses when a variety of complex conditions exist that make measurements of all the actual

[22] "ANTENNA INTRODUCTION/BASICS," n.d., <http://www.kyes.com/antenna/navy/basics/antennas.htm> (01 Sep 2009.

[23] "ANTENNA INTRODUCTION/BASICS," n.d., <http://www.tscm.com/antennas.pdf> (01 Sep 2009).

parameters impossible. Modeling allows the use of approximation methods to account for the abundant, varying influential parameters.[24]

The urban environment presents many unique influences or disruptions on radio wave transmissions. It is feasible to say that radio wave propagation in free space is almost completely understood and losses are simple enough to calculate and accurate enough to describe the propagation characteristics. The problem that arises in the urban environment is the impossibility that exists of knowing or predicting all of the factors involved that influence the transmission of radio waves to include the size, shape, spacing, and composition of all the buildings in the transmission path. Through the use of modeling in the urban environment, physical generalizations are made regarding factors such as building size and shape which enable more accurate predictions of areas of more complex urban geometry. Figure 1 shows the generally assumed configuration of a city for most of the urban propagation models.

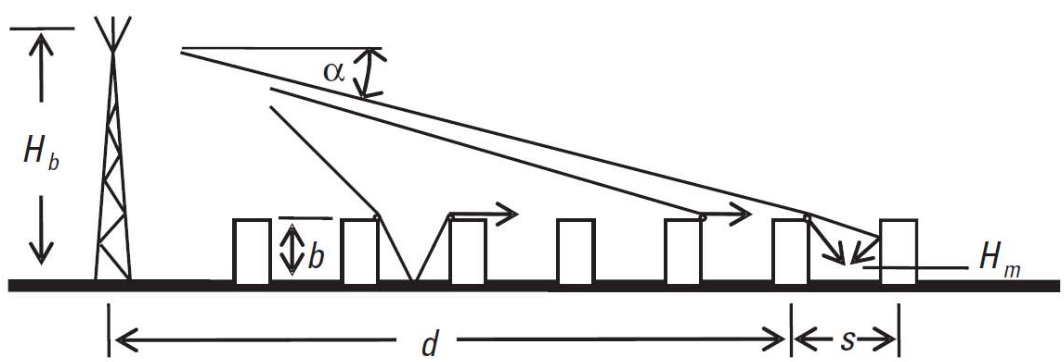


Figure 1. Generalized Urban Geometry Used In Models[25]

[24] Magdy Iskander, *Wireless Technologies and Information Networks* (Baltimore, MD: International Technology Research Instittue, 2000), 24.

In this example an average building height is used to represent the height of all the buildings in the propagation path (b). The base station antenna height ($H_b$) is above the average building height, there is an assumed average spacing between buildings (s), and the mobile station antenna ($H_m$) is usually within three meters of the ground, well below the average building height.[26]

### 1. Okumura Model

There have been many studies of radio wave propagation losses in the urban environment, dating back to 1935, but this study will focus on the widely accepted work of Yoshihisa Okumura. In 1968, Yoshihisa Okumura conducted thorough testing of radio wave propagation between base stations and mobile stations in and around Tokyo, Japan. Many tests were conducted with signals transmitted in scenarios with varying urban geometry. Measurements were made using frequencies of 200, 453, 922, 1310, 1430, and 1920 MHz. For each frequency tested, measured field strength values were plotted along path distances with varying conditions. Okumura and his colleagues developed a series of curves to fit this plotted data, representing the median attenuation extended along the transmission path as a function of frequency.[27]

Based on his data and calculations, Okumura developed a propagation model incorporating correction factors for the

[25] Kazimier Siwiak, *Radiowave Propagation and Antennas for Personal Communications* (New York, NY: Artech House, 2007), 201.

[26] Magdy Iskander, Wireless Technologies and Information Networks (Baltimore, MD: International Technology Research Institute, 2000), 24.

[27] A. G. Longley, *Radio Propagation in Urban Areas* (U.S. Department of Commerce, 1978), 9.

type of environment, city size, terrain type, and the locations of the transmit and receive antennas. His model was difficult and time consuming to use because each calculation required the user to physically refer to the Okumura mathematical curves to obtain losses and correction factors.

### 2. Hata Model

It was not until 1980 that Masaharu Hata simplified the Okumura model, developing a set of equations, reducing user input to only four parameters. With only frequency, transmitted distance, height of the base station antenna, and height of the mobile antenna, a fairly accurate prediction of propagation loss expected in the earlier Okumura model could be made. Some of the limiting factors that come with the simplicity of the Hata model are accurate predictions for only a short range of transmitted distances and frequencies. To overcome these limitations, many models have been developed as modifications of the Hata model to extend the accurate output over greater transmission distances and frequencies. The Hata model combines a logarithmic dependence on transmitted distance, a scaling term independent of distance, and correction factors for the urban environment types of open air, suburban, or urban. Other studies have shown that within the acceptable parameters, the Hata model closely matches the Okumura curves up to a transmission distance of about 30 km. Beyond 30 km, the two begin to separate, up to an approximately 15 dB difference near 100 km. The Hata model is the most

widely accepted urban propagation loss model in use today. Of the other existing propagation loss models, most use some form of the Hata Model.[28]

### 3. Hata Model for Urban Areas

The Hata Model for Urban Areas is the original Hata Model described above. It generally assumes that the transmission environment is urban in nature and provides a mobile station antenna height correction factor that is based on the size of the city and the frequency of the signal transmitted. Because the calculated losses from the Hata model begin to deviate from the Okumura curves beyond certain limits, the parameter ranges that ensure accuracy are a frequency between 150 and 1500 megahertz, a base station antenna height between 30 and 200 meters, a mobile station antenna height between one and ten meters, and a transmission distance between one and 20 kilometers. The mathematical calculations of the model will be discussed in Chapter III.[29]

### 4. Hata Model for Open Areas

Just as the name implies, the Hata Model for open areas is the most widely accepted propagation model used to calculated transmission losses in an open area. Although the definition of an open area is vague, during his studies in the late 1960s, Okumura defined an open area as one that is clear for a radius of 300 to 400 meters from the mobile

[28] *Investigation of Modified Hata Propagation Models* (Australian Communications Authority, 2001), 4.

[29] Kazimier Siwiak, Radiowave Propagation and Antennas for Personal Communications (New York, NY: Artech House, 2007), 208.

antenna station.[30] The Hata model for open areas is a function of the Hata model for urban areas plus a series of correction factors that reduce the loss based on logarithmic degrees of the transmission frequency and a constant which will always result in the open area loss being at least 40 dB less than the calculated urban area loss. A quick qualitative check would suggest that this equation is generally correct based on the fact that a much greater loss would be expected in an urban environment with buildings in the transmission path than a signal propagating through an open area. The input parameter limitations for the open area model are the same as the limitations for the urban Hata model. The mathematical calculations of the open area Hata model will be discussed in Chapter III.[31]

#### 5. Hata Model for Suburban Areas

Just like the Hata model for open areas, the Hata model for suburban areas is a derivative of the urban Hata model. Again, the quantitative limits of a suburban area are not clearly defined, but it seems to be recognized as a developed area outside the taller, denser concentration of structures in a bigger city. The suburban Hata Model is a function of the urban Hata model plus a correction factor that reduces the degree of loss based on a logarithmic factor of frequency plus a constant value that is only a small percentage of the constant applied to the open area model. The input parameter limitations for the suburban

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[30] A. G. Longley, Radio Propagation in Urban Areas (U.S. Department of Commerce, 1978), 9.

[31] Kazimier Siwiak, Radio wave Propagation and Antennas for Personal Communications (New York, NY: Artech House, 2007), 209.

area model are the same as the limitations for the urban Hata model. The mathematical calculations of the suburban area Hata model will be discussed in Chapter III.[32]

### 6. Extended Hata Model

With the advance of wireless communication systems, the fact that the maximum effective frequency of the Hata models was 1500 megahertz was a concern to many. A European group, Co-operative for Scientific and Technical Research (COST) formed a study committee (COST 231) to investigate the idea that the Hata model consistently underestimated path loss. As a result, COST 231 developed the COST Hata model or Extended Hata model to extend the acceptable input frequency parameter to 2000 megahertz. The Extended Hata model is similar to the regular Hata models, with some changes to the constant factors and an added 3 dB for large cities. This new model covers the frequency range from the upper end of the Hata model at 1500 megahertz to 2000 Megahertz, with the other parameters remaining the same. The mathematical calculations of the Extended Hata model will be discussed in Chapter III.[33]

### 7. Modified Hata Model

The most extreme alteration of the original Hata model is the Modified Hata model which allows for accurate loss predictions at frequencies up to 3000 megahertz and transmission distances up to 100 kilometers. Frequency

[32] Kazimier Siwiak, Radio wave Propagation and Antennas for Personal Communications (New York, NY: Artech House, 2007), 209.

[33] Robert Akl, *CCAP: CDMA Capacity Allocation and Planning* (St. Louis, MO: Washington University, 1998), 13.

transition values, corrections for the curvature of the earth, environmental corrections, height corrections, and a percentage of buildings value are all introduced in the modified Hata model. Although most studies show a consistent deviation from the Okumura curves, the Modified Hata model is the only one that closely represents the curves at an extended frequency and transmission distance. The mathematical calculations of the Modified Hata Model will be discussed in Chapter III.[34]

### 8. Walfisch – Ikegami Model

The Walfisch – Ikegami Model is recognized as the most accurate propagation loss prediction model, but the range of parameters that allow for accurate calculations is very small compared to the other models. This model has two different cases. The line-of-sight case is a simple equation with only two input parameters of transmission distance and frequency. The line-of-sight calculation produces losses just slightly greater than the free space losses. Again, a quick qualitative check would validate the idea that an unobstructed signal would encounter losses similar to those in free space. The second, non-line-of-sight equation is much more complicated, starting with the free space loss and introducing factors that account for the average roof top height, a multi-screen diffraction, building separation, street width, relationship between antenna heights, rooftop to street diffraction, and street orientation angle. The acceptable input frequency range for

[34] “Modified Hata Model,” 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/Modified ModifiedH.htm> (23 Aug 2009).

this model is higher than most at 800 to 2000 megahertz, but the transmission distance range is only .02 to 5 kilometers. The mathematical calculations of the Walfisch-Ikegami model will be discussed in Chapter III.[35]

## E. APPLYING THE RADIO WAVE PROPAGATION MODELS

Most of this literature review and the remainder of this study are focused on the mechanics of the radio wave propagation models and how to actually go about calculating the propagation losses without an in depth look at how to actually apply the calculated losses. The focus will continue to remain on methods to determine the most accurate losses, but the following excerpt from a dissertation on **Radio Wave Diffraction and Scattering Models for Wireless Channel Simulation** by Mark D. Casciato sums up the need for such calculations:

> Accurate prediction of these propagation effects allows the communications system engineer to address the trade-off between radiated power and signal processing by developing an optimum system configuration in terms of modulation schemes, coding, frequency band and bandwidth, antenna design, and power.[36]

[35] "Cost 231 Walfisch-Ikegami Model," 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/costWI.ht> (23 Aug 2009).

# III. MODELING

## A. REQUIREMENTS

Based on the literature review conducted by this research effort, a need exists for a simple tool that takes operator input of urban environmental and transmission parameters, and determines the best-fit propagation loss model from those available, calculates the associated loss, demonstrates the variation in the calculated losses of selected models, and provides guidance on the impact of adjusting transmission parameters. Throughout the research phase, two propagation loss calculators were discovered, but the author could not find a single source that compared the calculated losses of various models demonstrating their differences and the relationship to free space losses over a range of potential input parameters.

## B. VISION

Based on the above requirements, the vision of this study is focused on developing a tool that not only provides a test bed for validating propagation loss scenarios through the use of several different models, but also allows a user to input a variety of parameters to determine potential losses associated with an actual environment along with computation of the impact of altering any of the controllable factors. From the user perspective, there will be two sections to this conceptual propagation loss

[36] Mark Casciato, “Radio Wave Diffraction and Scattering Models For Wireless Channel Simulation,” University of Michigan (2001): 1.

assessment tool. The first section will be an <u>input page</u> on which the user enters environmental and transmission parameters that are required by the selected propagation loss models. A chart will be provided informing the user of valid ranges for each of the parameters. The second section of the tool will be an <u>output page</u> which displays the actual calculated losses associated with each of the selected models, graphical representations of those calculations carried out over a range of frequencies and distances, and a portion of the screen displaying the propagation loss model that best fits the input parameters followed by the mathematical equation involved in that "best fit" model. There will also be several calculation pages in which all the parameters entered on the Input page will be used to derive the results that eventually are displayed on the Output page. Each section will be covered throughout the developmental phase in detail in the descriptions that follow. Once the tool is developed, various tests will be conducted in an effort to associate particular propagation loss models as possible "best fits" for certain environments. Other data and sources will be used to validate the tool and an instruction guide, or user's guide, will be produced to walk a user through each step in an effort to make this a potential operational tool that would find widespread use by a large number of users.

## C. HARDWARE

All work in this study will be conducted on a personal computer with no need for actual physical experimentation.

## D. SOFTWARE

The primary software program used in this study will be Microsoft Excel. A complex spreadsheet will be developed to achieve the above stated goals. Due to the empirical nature of all the work involved in this study, all models, formulas, equations, and validation tools come from online sources or printed documents.

## E. INPUT PARAMETERS

Based on the models selected above, there are 13 user inputs that are required to establish the conditions needed to perform all the calculations in predicting the propagation losses. Each of those inputs is described below.

### 1. Base Station Antenna Height

The height of the base station antenna is a measurement of the distance from the ground to the top of the antenna. In many cases, the antenna will be mounted on the roof of a building, but the measurement will always be from the ground. For the propagation loss models being used, **the base station antenna height must fall in the range of 4 to 300 meters**. Values entered that fall outside of that range will not produce entirely wrong results, but the accuracy will begin to degrade.

### 2. Mobile Station Antenna Height

The height of the mobile station antenna is a measurement of the distance from the ground to the antenna. In most cases, the mobile station antenna will be a handheld

device or mounted to a vehicle. The models in this study will ensure accurate loss calculations with **mobile station antenna heights up to 10 meters** but will begin to degrade after that.

### 3. Distance Between Base Station and Mobile Station

This measurement is the shortest over the ground distance between the two stations regardless of obstacles or terrain in between these two points (i.e., line-of-sight). To ensure accuracy with the selected models **the transmission distance should be between 0.02 and 100 kilometers (km)**.

### 4. Environment

This parameter is a qualitative assessment of the environment and can be described as urban, suburban, or open area. Although there are no specific quantitative guidelines defining each category, Okumura’s definitions used back in the 1960s provide a general reference. He described an open area as one that is clear for at least 300 to 400 meters around the mobile station, a suburban area as a built up region of houses and trees, and an urban area as any region built up more than a suburban area.[37]

### 5. City Size

The city size is another qualitative parameter divided into categories of small, medium, and large. Some of the quantitative limitations used in the 1960s are outdated due to urban growth over the past 40 years. Because of

[37] A. G. Longley, Radio Propagation in Urban Areas (U.S. Department of Commerce, 1978), 9.

potential uncertainty in selecting the size of a city, experimentation will be conducted to determine the impact of city size on the loss calculations.

### 6. Percentage of Buildings

This parameter is the percentage of the area of actual structures compared to the entire area of the city. It is a figure used only in the Modified Hata model with **an acceptable range of 3 to 50 percent**. If this value is unknown, an approximation can be applied or a median value of 25 percent can be used. The building percentage is another potential uncertainty that will drive tests to evaluate the effects of adjusting this parameter.[38]

### 7. Average Height of Buildings in Area

The average height of the buildings in the transmission path is used in the Walfisch–Ikegami model. This is the only model that accounts for the fact that the base station antenna may actually be below the height of the buildings in the transmission path, which would significantly increase the loss.[39]

### 8. Building Separation

The building separation is the average spacing, in meters, between the centers of the buildings in the transmission path. This parameter is used in the Walfisch–

[38] “Modified Hata Model,” 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/Modified ModifiedH.htm> (23 Aug 2009).

[39] "Cost 231 Walfisch-Ikegami Model," 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/costWI.h ht> (23 Aug 2009).

Ikegami model, and only if the average width of the streets is unknown. If the average building separation is unknown, a value between 30 and 50 meters should be used.[40]

### 9. Width of Street

The average width of the streets is used in the Walfisch-Ikegami model to calculate the rooftop to street diffraction and scatter loss. If street width is unknown, an approximation should be made by dividing the average building separation distance by two.[41]

### 10. Antenna Gain

The gain of each antenna is used to calculate the free space loss given the other transmission parameters, to help demonstrate the impact of the urban environment on the overall transmission loss.

### 11. Line-Of-Sight or Obstructed

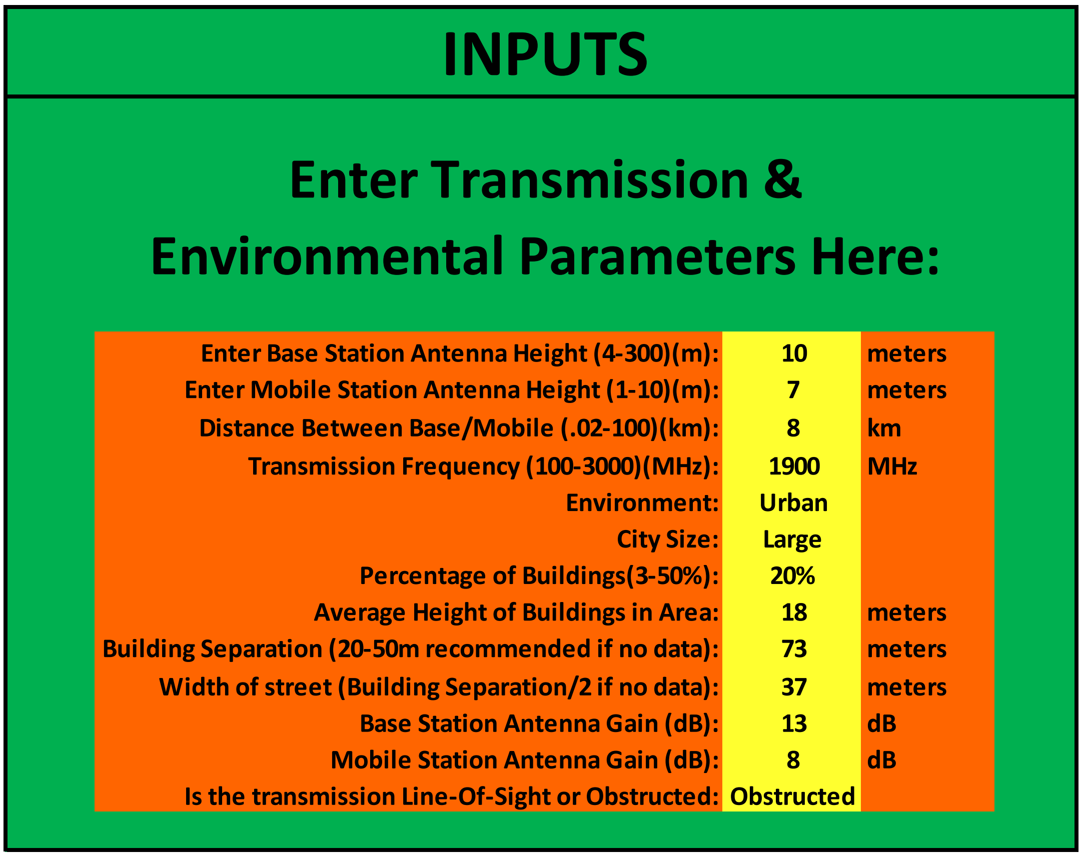
This value is a simple judgment call on whether or not there are any obstacles between to the two antennas. It is used for the Walfisch-Ikegami model. If in fact the transmission path is line-of-sight, the equation is a simple one with a resultant loss just slightly higher than the associated free space loss.

[40] "Cost 231 Walfisch-Ikegami Model," 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/costWI.h ht> (23 Aug 2009).

[41] Ibid.

## F. PROPAGATION LOSS TOOL INPUT

Figure 2 shows a snapshot of the propagation loss tool input page. All the adjustable blocks are yellow in color. To alleviate any confusion or errors that may arise due to potential misspellings, all of the qualitative parameter fields have been designed with drop down boxes, allowing the user to select the correct option rather than typing it.


INPUTS

Enter Transmission & Environmental Parameters Here:

| | | |
|---|---|---|
| Enter Base Station Antenna Height (4-300)(m): | 10 | meters |
| Enter Mobile Station Antenna Height (1-10)(m): | 7 | meters |
| Distance Between Base/Mobile (.02-100)(km): | 8 | km |
| Transmission Frequency (100-3000)(MHz): | 1900 | MHz |
| Environment: | Urban | |
| City Size: | Large | |
| Percentage of Buildings(3-50%): | 20% | |
| Average Height of Buildings in Area: | 18 | meters |
| Building Separation (20-50m recommended if no data): | 73 | meters |
| Width of street (Building Separation/2 if no data): | 37 | meters |
| Base Station Antenna Gain (dB): | 13 | dB |
| Mobile Station Antenna Gain (dB): | 8 | dB |
| Is the transmission Line-Of-Sight or Obstructed: | Obstructed | |

Figure 2. Propagation Loss Tool Input Page

The second half of the input page is simply a reference providing users with the acceptable ranges for each of the parameters. Parameters entered on the input page that fall outside these limitations will result in calculated losses

that begin to deviate in accuracy. A snapshot of the parameter range page is displayed in Figure 3.

**Parameter Ranges for Each Model**

| Model | Base Station Height Min/Max (m) | | Mobile Station Height Min/Max (m) | | Distance Min/Max (km) | | Frequency Min/Max (MHz) | | Environment | City Size |
|---|---|---|---|---|---|---|---|---|---|---|
| Hata (Open) | 30 | 200 | 1 | 10 | 1 | 20 | 150 | 1500 | Open | N/A |
| Hata (Suburban) | 30 | 200 | 1 | 10 | 1 | 20 | 150 | 1500 | Suburban | N/A |
| Hata (Urban) | 30 | 200 | 1 | 10 | 1 | 20 | 150 | 1500 | Urban | Any |
| Modified Hata | 30 | 300 | 1 | 10 | 1 | 100 | 100 | 3000 | Urban | Any |
| COST Hata | 30 | 200 | 1 | 10 | 1 | 10 | 1500 | 2000 | Urban | Any |
| Walfisch-Ikegami | 4 | 50 | 1 | 3 | 0.02 | 5 | 800 | 2000 | Urban | Any |

Figure 3. Propagation Loss Model Parameter Ranges

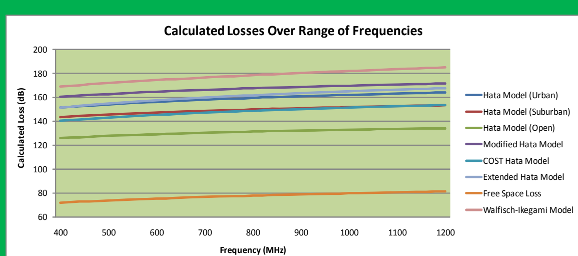
## G. PROPAGATION LOSS TOOL OUTPUT

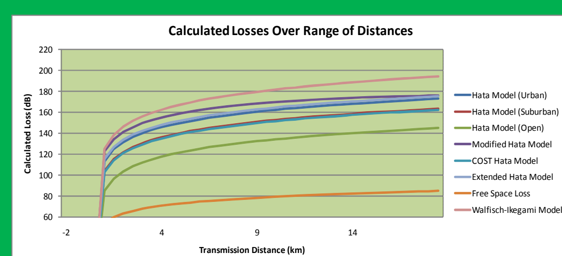
**Comparision of Propagation Loss Models**

**OUTPUT**

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | Extended Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 159.54 dB | 149.90 dB | 131.44 dB | 167.59 dB | 148.80 dB | 77.93 dB | 178.55 dB |




Based on your parameters, the best model to use is the: **Hata Model (Urban)** (with errors)

Some of your parameters are outside the acceptable ranges for this model.

Model: Hata (Urban)

LU = 69.55 + 26.16*log(f) - 13.82*log(hB) - CH + (44.9 - 6.55*log(hB))*log(d)

For large cities:

CH = 8.29*(log(1.54*hM))^2 - 1.1, if 150 ≤ f ≤ 200

3.2*(log(11.75*hM))^2 - 4.97, if 200 ≤ f ≤ 1500

For small or medium cities:

CH = 0.8 + (1.1*log(f) - 0.7)*hM - 1.56*log(f)

Where,

LU = Path loss in Urban Areas (dB)

hB = height of base station antenna (m)

hM = height of mobile station antenna (m)

f = frequency of transmission (MHz)

CH = antenna height correction factor

d = distance between the base station and mobile station (km)

Figure 4. Propagation Loss Tool Output Page

An overview of the layout of the Propagation Loss Tool Output page is shown in Figure 4. The upper left corner of Figure 4, containing the yellow boxes is the section that displays the actual calculated losses associated with each of the selected models. Below that, two graphs display the calculated losses for each model carried out over a range of frequencies and transmission distances. The bottom half of Figure 4 is the part of the Output page that displays the best fit propagation loss model, given the input parameters, and the calculations associated with that model. Each section will be displayed and discussed in greater detail.

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | Extended Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 159.54 dB | 149.90 dB | 131.44 dB | 167.59 dB | 148.80 dB | 77.93 dB | 178.55 dB |

Figure 5. Calculated Propagation Losses

A more detailed view of the calculated loss section of the output page is displayed in Figure 5. This study involves the use of seven other pages of formulas and calculations to derive the propagation losses that were used by the program and are ultimately outputted in this section. The purpose of this section is to display the actual loss numbers that are calculated using each of the different models. Given the parameters that the user enters on the Input page, these numbers represent the actual mathematical results achieved when the set of input parameters are plugged into the published equations of each model. The availability of these results allows the user to compare the

losses associated with each model and the free space loss at the input specified frequency and distance.

Once the Propagation Loss Tool is completely developed, the input parameters will be manipulated to show the effects on the calculated losses from each model.  To provide a better understanding of the losses from Figure 5, the next section of the Output page shows a graphical representation of the relationships of each of these losses.  The center of the graph in Figure 6 shows the actual losses calculated above at the frequency entered on the input page.  Those losses are then extended out and calculated over a range of frequencies both to the left and right of the input frequency and displayed in the graph to demonstrate how altering the transmission frequency would affect the calculated losses with all the other input parameters held constant (the plot below, for example, extends from a low frequency limit of 400 MHz to an upper frequency limit of 1.2 GHz) for a specified input frequency of 800 MHz.

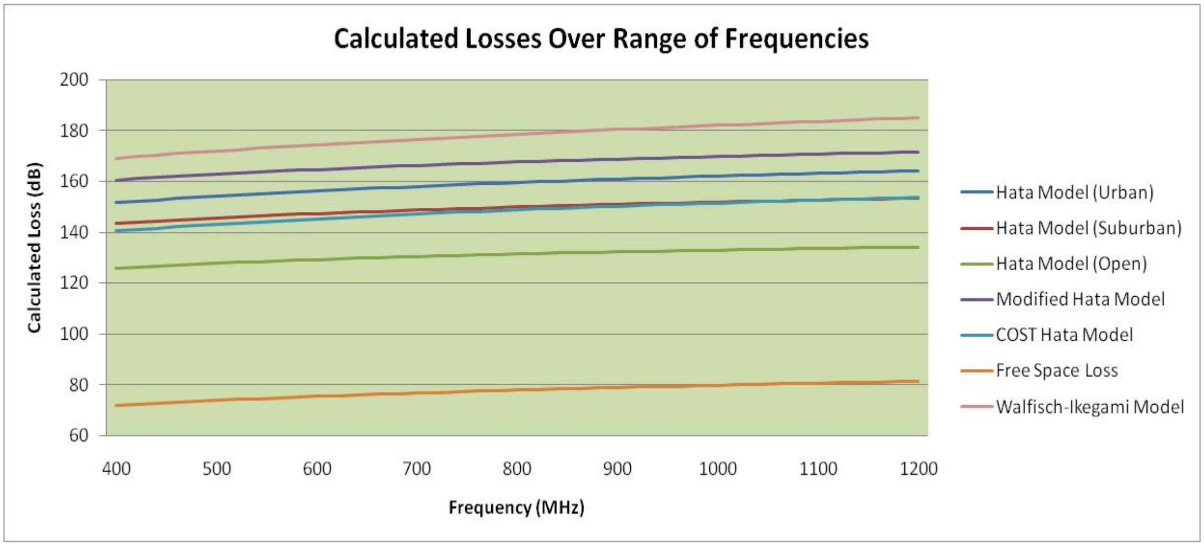



Figure 6.     Propagation Path Losses VS Frequency

Figure 7 is a similar graph from the Output page that uses a different abscissa parameter in that it shows the actual losses extended out and calculated over a range of distances to the left and right of the input distance to demonstrate how altering the transmission distance would affect calculated losses with all the other input parameters held constant. The calculations used to derive both graphs will be discussed in further detail.

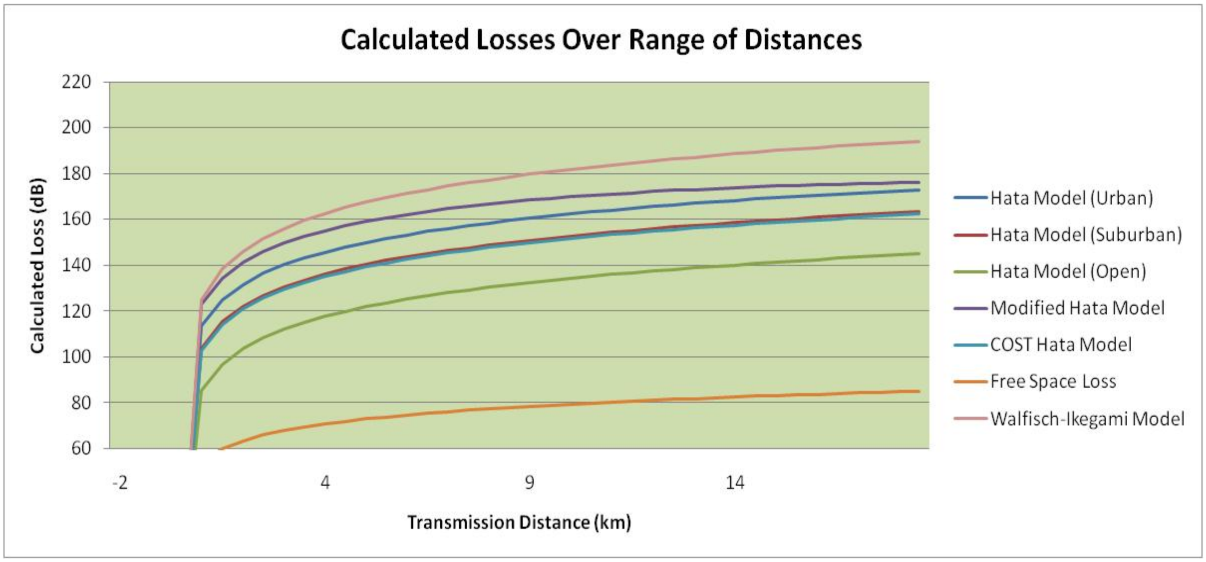



Figure 7. Propagation Losses vs Distance

## H. UNITS

### 1. Power Gain and Loss

All power measurements and calculations in this study are expressed in decibels (dB). The decibel (dB) measurement is a method used to describe a gain or loss in a communication system, allowing for addition and subtraction rather than multiplication and division. In the case of power, the decibel expression is a ratio comparison of the

power of two entities. For the radio wave transmission scenarios used in this study, the loss expression is the ratio of the power received at the mobile station antenna compared to the power transmitted at the base station antenna expressed as:

$$\text{Power Loss (dB)} = 10*\log\left(\frac{\text{Mobile Station Antenna Power Received}}{\text{Base Station Antenna Power Transmitted}}\right)$$

### 2. Antenna Height and Urban Dimensions

In this study, antenna heights, building heights, separation of buildings, and street widths are all expressed in meters (m).

### 3. Transmission Distance

The distance between the base station antenna and the mobile station antenna is measured in kilometers (km).

### 4. Transmission Frequency

All frequencies in this study are expressed in megahertz (MHz).

## I. PROPAGATION LOSS MODELS

Although there are many propagation loss models that have been developed over the past 40 years, the focus of this study will be on a select few that are all in some way an iteration of the Hata model which is based on the work of Yoshihisa Okumura. The project will use the urban, suburban, and open versions of the Hata model, the Modified Hata model, the COST (extended) Hata model, the Walfisch-Ikegami model, and compare them all to the free space loss.

Each model to be used will be discussed in detail below followed by an explanation of how the calculations are going to be reproduced in the Propagation Loss Tool on Microsoft Excel.

### 1. Hata Model for Urban Areas

**Model: Hata (Urban)**

$$L_U = 69.55 + 26.16*\log(f) - 13.82*\log(h_B) - C_H + (44.9 - 6.55*\log(h_B))*\log(d)$$

**For large cities:**

$$CH = 8.29*(\log(1.54*h_M))^2 - 1.1, \quad \text{If } 150 = f = 200$$

$$3.2*(\log(11.75*h_M))^2 - 4.97, \quad \text{If } 200 = f = 1500$$

**For small or medium cities:**

$$CH = 0.8 + (1.1*\log(f) - 0.7)*h_M - 1.56*\log(f)$$

**Where,**

**$L_U$ = Path loss in Urban Areas (dB)**
**$h_B$ = height of base station antenna (m)**
**$h_M$ = height of mobile station antenna (m)**
**f = frequency of transmission (MHz)**
**CH = antenna height correction factor**
**d = distance between the base station and mobile station (km)**

Figure 8. Hata Model for Urban Areas[42]

To obtain a radio wave propagation loss using the urban Hata model, five input parameters are required: base station antenna height, mobile station antenna height, frequency, distance, and the size of the city. By using this model, it is assumed that the environment type is actually urban. **Applying this model to an open area or suburban area will result in an estimated propagation loss**

[42] *Investigation of Modified Hata Propagation* Models (Australian Communications Authority, 2001), 4.

**significantly larger than the actual loss.** As shown in Figure 8, the first step involves calculating an antenna height correction factor, CH, as a logarithmic function of frequency and accounting for the height of the mobile antenna. The actual equation for CH depends on the size of the city and the frequency. Once the antenna correction factor is known, the overall loss can be calculated using the top equation in Figure 8. In the Excel Propagation Tool, a series of logic functions were used to determine all of the input parameters for the final equation in the urban Hata Model.

### 2. Hata Model for Suburban Areas

**Model: Hata (Suburban)**

$L_{SU} = L_U - 2*(\log(f/28)^2 - 5.4$

$L_u = 69.55 + 26.16*\log(f) - 13.82*\log(h_B) - C_H + (44.9 - 6.55*\log(h_B))*\log(d)$

**For large cities:**

$CH = 8.29*(\log(1.54*h_M))^2 - 1.1, \quad \text{if } 150 = f = 200$

$3.2*(\log(11.75*h_M))^2 - 4.97, \quad \text{if } 200 = f = 1500$

**For small or medium cities:**

$CH = 0.8 + (1.1*\log(f) - 0.7)*h_M - 1.56*\log(f)$

**Where,**

**$L_{SU}$ = Path loss in Suburban Areas (dB)**

**$L_U$ = Path loss in Urban Areas (dB)**

**$h_B$ = height of base station antenna (m)**

**$h_M$ = height of mobile station antenna (m)**

**f = frequency of transmission (MHz)**

**CH = antenna height correction factor**

**d = distance between the base station and mobile station (km)**

Figure 9. Hata Model for Suburban Areas[43]

[43] Kazimier Siwiak, Radio wave Propagation and Antennas for Personal Communications (New York, NY: Artech House, 2007), 209.

The Hata Model for suburban areas shown in Figure 9 is a derivative of the urban Hata Model. The same input parameters and calculations are used to calculate the urban Hata loss, but then an additional logarithmic factor of the function and a constant are used to reduce the loss for the suburban are as shown in the first equation of Figure 9.

### 3. Hata Model for Open Areas

**Model: Hata (Open)**

$$L_O = L_U - 4.78*(\log(f)^2) + 18.33*\log(f) - 40.94$$

$$L_U = 69.55 + 26.16*\log(f) - 13.82*\log(h_B) - C_H + (44.9 - 6.55*\log(h_B))*\log(d)$$

**For large cities:**

$$CH = 8.29*(\log(1.54*h_M))^2 - 1.1, \quad \text{If } 150 = f = 200$$

$$3.2*(\log(11.75*h_M))^2 - 4.97, \quad \text{If } 200 = f = 1500$$

**For small or medium cities:**

$$CH = 0.8 + (1.1*\log(f) - 0.7)*h_M - 1.56*\log(f)$$

**Where,**

**$L_O$ = Path loss in Open Areas (dB)**
**$L_U$ = Path loss in Urban Areas (dB)**
**$h_B$ = height of base station antenna (m)**
**$h_M$ = height of mobile station antenna (m)**
**f = frequency of transmission (MHz)**
**CH = antenna height correction factor**
**d = distance between the base station and mobile station (km)**

Figure 10. Hata Model for Open Areas[44]

Just like the suburban Hata model, the Hata model for open areas uses the urban Hata model and applies a logarithmic function of the frequency and a constant correction factor to reduce the calculated loss for the open

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[44] Kazimier Siwiak, Radio wave Propagation and Antennas for Personal Communications (New York, NY: Artech House, 2007), 209.

area environment. The corrections were based on empirical fits to measured data in the urban, suburban and open environments. The calculations involved in the open area Hata model are shown in Figure 10.

### 4. COST (Extended) Hata Model

**Model: COST Hata**

$$L = 46.3 + 33.9*\log(f) - 13.82*\log(h_B) - a(h_M) + (44.9 - 6.55*\log(h_B))*\log(d) + C$$

$$a(h_M) = (1.1*\log(f) - 0.7)*h_R - 1.56*\log(f) - 0.8$$

**C = 0 dB for small cities, medium cities, and suburban areas**
**3 dB for metropolitan areas**

**Where,**
**L = Path Loss (dB)**
**f = Frequency of Transmission (MHz)**
**$h_B$ = height of base station antenna (m)**
**$h_M$ = height of mobile station antenna (m)**
**d = distance between the base station and mobile station (km)**
**$a(h_M)$ = mobile station antenna height correction factor**

Figure 11. COST (Extended) Hata Model[45]

The COST Hata model shown in Figure 11 uses the same mobile station antenna height correction factor as all the other three Hata models, but applies an entirely different set of functional parameters and an additional correction factor that is more appropriate for large cities.

[45] Robert Akl, *CCAP: CDMA Capacity Allocation and Planning* (St. Louis, MO: Washington University, 1998), 13.

### 5. Modified Hata Model

**Model: Modified Hata**

$L_{MH} = L_U + S_o + a_z + S_m + B_o$

$L_U = 69.55 + 26.16*\log(f) - 13.82*\log(h_B) - C_H + (44.9 - 6.55*\log(h_B))*\log(d)$

For large cities: $CH = 8.29*(\log(1.54*h_M))^2 - 1.1$, If $150 = f = 200$

$3.2*(\log(11.75*h_M))^2 - 4.97$, If $200 = f = 1500$

For small/medium cities: $CH = 0.8 + (1.1*\log(f) - 0.7)*h_M - 1.56*\log(f)$

$S_o = (1 - U_r)((1 - 2*U_r)L_O + 4*U_r*L_{SU})$

$U_r = 0$ for open area, .5 for suburban, 1 for urban

$U = 0$ for small/medium city, 1 for large city

$L_{SU} = L_U - 2*(\log(f/28))^2 - 5.4$

$L_O = L_U - 4.78*(\log(f)^2) + 18.33*\log(f) - 40.94$

$F_1 = (300^4)/(f^4 + 300^4)$ $F_2 = (f^4)/(f^4 + 300^4)$

$S_m = (27+(f/230))*\log((17*(h_B + 20))/(17*(h_B + 20) + d^2)) + 1.3 - (|f-55|/750)$

$B_o = 25*\log(B_1)-30$

$a_z = (1-U)*(0.8 + (1.1*\log(f) - 0.7)*h_M - 1.56*\log(f)) + ((8.29*(\log(1.54*h_M))^2$
$- 1.1)*F_1 + (3.2*(\log(11.75*h_M))^2 - 4.97)*F_2)$

Where,

$L_{MH}$ = Path Loss (dB)

$L_{SU}$ = Path loss in Suburban Areas (dB)

$L_O$ = Path loss in Open Areas (dB)

$L_U$ = Path loss in Urban Areas (dB)

$h_B$ = height of base station antenna (m)

$h_M$ = height of mobile station antenna (m)

f = frequency of transmission (MHz)

CH = antenna height correction factor

d = distance between the base station and mobile station (km)

$S_o$ = Suburban/Urban Correction

$B_1$ = Percentage of Buildings

$F_1$, $F_2$ = High Frequency transition values

$a_z$ = overall height correction factor

Figure 12. Modified Hata Model[46]

The Modified Hata model in Figure 12 is a complex model that produces the most accurate propagation losses for a

[46] "Modified Hata Model," 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/Modified ModifiedH.htm> (23 Aug 2009).

small range of parameters. The first step in this process is to calculate the percentage of buildings factor based on the percentage of buildings entered on the input page. Two high frequency transition values are determined as a function of varying degrees of the frequency. Next, an overall height correction factor is calculated as a function of frequency and mobile antenna height. Corrections for the earth’s curvature and a suburban/urban correction are both applied. The final equation in the Modified Hata model shown at the top of Figure 12 applies iterations of the urban, suburban, and open area Hata models along with all of these correction factors to achieve a fairly accurate propagation loss prediction out to 100 kilometers and up to 3000 megahertz. Building this model into the Propagation Loss Tool on Microsoft Excel is a complex process requiring a series of 16 embedded logic functions that test the parameter values against algorithmic ranges and adjusts the calculations accordingly.

## 6. Walfisch-Ikegami Model

**Model: Walfisch-Ikegami**

$L_{WI} = L_o + L_{rts} + L_{msd}$

$L_o = 20*\log(d) + 20*\log(f) + 32.44$

$L_{rts} = -16.9 - 10*\log(w) + 10*\log(f) + 20*\log(h_{roof} - h_M) + L_{ori}$

Assuming $f=90$ $L_{ori} = .01$

$L_{msd} = L_{bsh} + k_a + k_d*\log(d) + k_f*\log(f) + 9*\log(b)$

$L_{bsh} = -18*\log(1+h_B - h_{roof})$ for $h_b > h_{roof}$, $L_{bsh} = 0$ for otherwise

$k_a = 54$ for $h_b = h_{roof}$

$k_a = 54 - 0.8*(h_b - h_{roof})$ for $d = 0.5$ and $h_b = h_{roof}$

$k_a = 54 - 0.8*(h_b - h_{roof})*(d/0.5)$ for $d < 0.5$ and $h_b = h_{roof}$

$k_d = 18$ for $h_b > h_{roof}$

$k_d = 18 - 15*(h_b - h_{roof})/h_{roof}$ for $h_b = h_{roof}$

$k_f = -4 + .7*(f/925 - 1)$ for suburban, small cities, medium cities

$k_f = -4 + 1.5*(f/925-1)$ for metropolitan areas

$L_{W\,los} = 42.6 + 25*\log(d) + 20*\log(f)$ when Line-of-sight and $d = 0.02$ km

Where,

$L_{WI}$ = Path Loss (dB)

$L_{W\,los}$ = Line of Sight Pat Loss (dB)

$L_o$ = Free Space Path Loss (dB)

$L_{rts}$ = Roof to Street Loss (dB)

f= Frequency of Transmission (MHz)

$h_B$ = height of base station antenna (m)

$h_M$ = height of mobile station antenna (m)

d = distance between the base station and mobile station (km)

w = average width of roads (m)

b = average building separation (m)

$h_{roof}$ = average height of buildings along path

$k_a$, $k_d$, $k_f$ = correction factors

Figure 13. Walfisch-Ikegami Model[47]

[47] "Cost 231 Walfisch-Ikegami Model," 15 Feb 2001, <http://www.ee.bilkent.edu.tr/~microwave/programs/wireless/prop/costWI.hht> (23 Aug 2009).

The Walfisch-Ikegami model is another complex inter-related set of calculations with many different correction factors. The first step in the Walfisch-Ikegami model is to determine whether the transmission path is obstructed, or line-of-sight. If the path is in fact line-of-sight, the model is quite simple and very similar to that achieved when calculating free space propagation loss. If the path is obstructed, the first step is to calculate the three k correction factors that account for the relationship of the base antenna height to the average height of the roofs in the path of transmission, and multi-screen diffraction loss versus frequency and distance. A roof to street loss is then calculated and added to the multi-screen diffraction loss with the free space loss to equal the total propagation loss according to the Walfisch-Ikegami model in Figure 13. As was the case for the Modified Hata model, this model (Walfisch-Ikegami) also requires a great deal of embedded logic functions when entered into Microsoft Excel.

## J. PROPAGATION LOSS TOOL RESULTS

### 1. Loss Calculations

The first goal of developing the Propagation Loss Tool is to calculate expected propagation losses associated with each of the selected models. Once all of the above equations for each model are entered into Microsoft Excel, the parameters entered by the user on the Input page (Figure 3) will be linked to all of these equations. Although the calculations are complex and many factors are embedded or reliant on other equations, the output will be the same as working the math problems of each model out by hand.

Essentially this first process of the Propagation Loss Tool is developing a type of propagation loss calculator that implements the defining equations.

### 2. Demonstrate Variation in Output of Each Model

Demonstrating the different calculated losses from each model is accomplished in two different ways with the Propagation Loss Tool. The first method is through the display of the actual calculated losses resulting from each of the models as shown earlier in Figure 4. This provides a numerical comparison of the output produced by each model. Although it does not provide indications of whether or not the parameters for each model are within the acceptable limits that ensure accurate results, it still shows the general spread of the results. The second method for demonstrating the computed losses is through the use of the two graphs on the Output page. Both graphs provide more of a visual relationship with values extended out over ranges of distance and frequency, allowing for easy observation of the trends of the losses associated with each model. This second method is expected to provide a better method of useable output data format for the general user.

### 3. Determining the Best Fit Model

To determine the model that best represents the most accurate propagation loss prediction, a series of criteria will be developed to categorize the parameters entered by the user. Selections will be based on the relationship of the input parameters and the published parameter limitations that ensure accuracy for each model. The details and development of this process will be discussed in Chapter IV.

### 4. Impact of Varying Parameters

The final objective of the Propagation Loss Tool is to demonstrate the impact of varying certain parameters on the expected propagation loss. For these tests, one parameter will be adjusted across the range of the published limits while keeping all other parameters constant within the limits of the various models. The intent of this test is to give the user an idea of the value associated with altering parameters that are in fact adjustable and showing the significance of the unchangeable parameters in the loss calculations. These variation tests and the results will be covered in detail in Chapter IV.

### 5. Validation

The last step in this study will be to validate the Propagation Loss Tool and prove that the derived information is useful and to a certain degree, accurate. This will be accomplished by comparing results to other propagation loss software and if available, existing data.

# IV. RESULTS

## A. DETERMINING THE BEST MODEL

Figure 14 is a flow chart developed in support of this study, depicting the methodology for choosing the propagation loss model producing the most accurate loss prediction based on the given parameters. Although there is no real way to validate these results without gathering exact measurements of the given urban environment and conducting radio transmission tests in the field, the acceptable parameter limitations for each model, which ensure close proximity to the Okumura data curves (which served as the foundation for all other model developments), help to categorize the inputted scenarios. Some of the scenarios will be paired with certain models based on environment type by using a common sense approach, while others will require a more in depth evaluation of all of the parameters.

The first step in choosing the “best model” is to evaluate the environment type. If the environment is an open area, the recommended model to use is the Hata model for open areas. All the other models will result in losses much greater than can be expected. An excessive loss model result could lead to conditions where the user would adopt too much conservatism, or perhaps build a more expensive end-to-end system than necessary. Because of the selection for an inappropriate environment model, the user will be informed that the model of choice is the Hata model for open areas. If any of the parameters fall outside of the

accepted parameter ranges from the chart on the Input page in Figure 3 for the open area model, then the user will be notified that the open area Hata model is still the best fit model, but that the result will have a certain degree of inaccuracy due to one or more extreme parameter values.

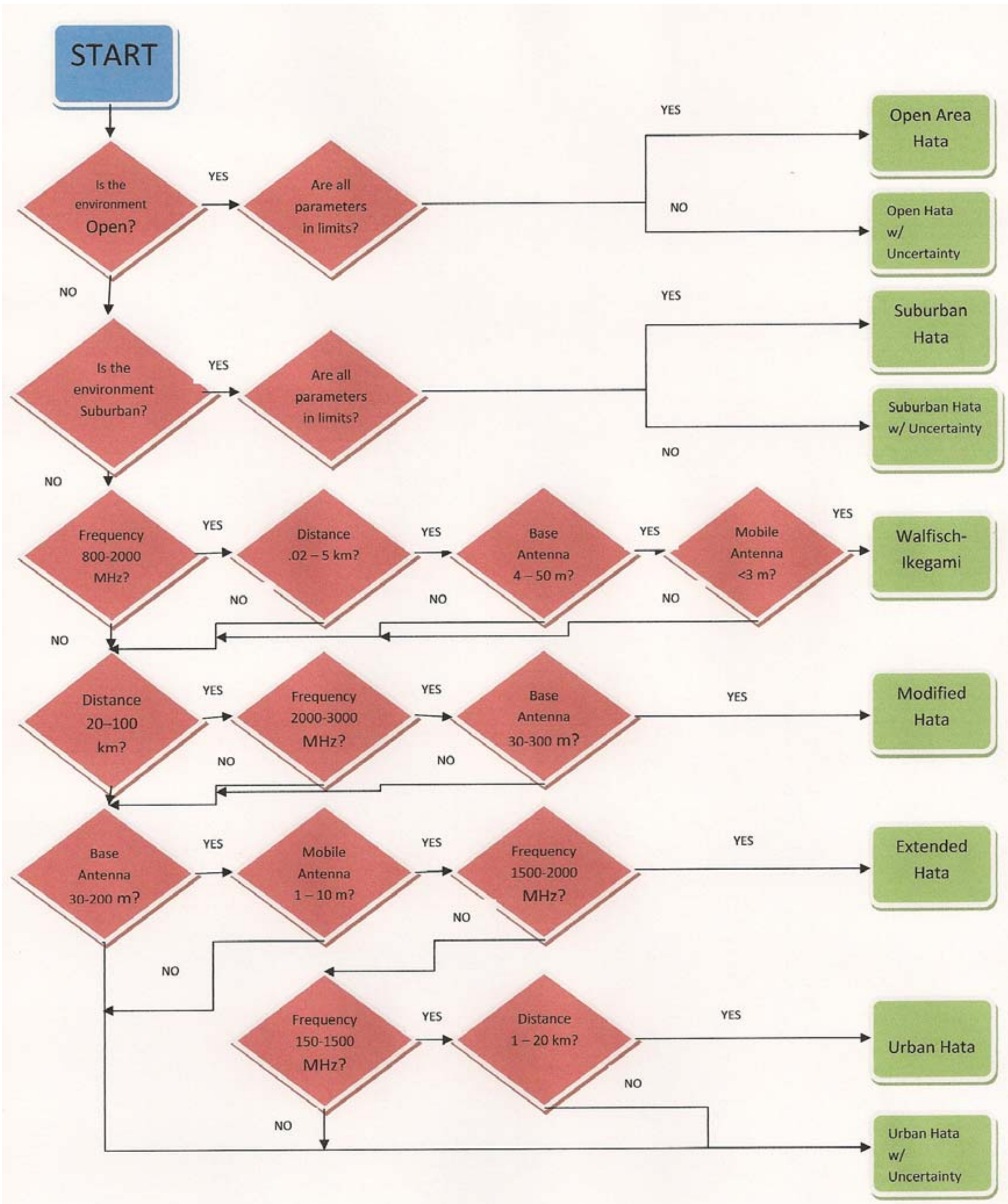



Figure 14. Best Model Classification Flowchart

If the environment type is suburban, the recommended model will be the Hata model for suburban areas. Just like with the open area Hata model, using any of the other models would result in calculated losses much higher than the actual expected loss. The same display format will be used informing the user that the best model to use is the suburban Hata model with an indication of inaccuracy if any of the parameters fall outside the provided limits.

The next steps get more complicated. The Walfisch-Ikegami model is claimed in the literature to be one of the most accurate models at predicting propagation losses, but it is also the most restrictive in its range of valid parameters. Because of the parameter restrictions, it is the first one to be tested against the input parameters. If the frequency falls within the acceptable range, then the distance is checked. If the distance is in range, the base station antenna height is checked. If the base antenna height is acceptable, the mobile station antenna height is checked. If all of those parameters are within the designated ranges, then the Walfisch-Ikegami model is displayed to the user as the best model to use. If any of the parameters fall outside the accepted ranges, then the process is carried on to the next test to determine if the Modified Hata model is the model of choice. The Modified Hata is next because it encompasses the highest range of values for transmission frequencies and distances. If the parameters do not fall within the Modified Hata range windows, the next test is for the COST (extended) Hata Model. By first determining if the given scenarios meet the criteria of these models that encompass the extreme cases of parameter combinations, the process will eventually narrow

the options down to only the urban Hata model. If the inputted parameters do not meet the criteria for any of the models, the recommended model will be the urban Hata model with the disclaimer that the resultant loss will have a certain degree of inaccuracy due to one or more outlying parameters.

After the conditions of the flow chart in Figure 14 were established, the mechanics of that process were entered into the Propagation Loss Tool developed in this study using a series of embedded Excel logic functions. Each potential result was then attached to a graphic display of the selected best fit model with the equations used to calculate the resultant loss of that model. These graphics associated with each model are then displayed on the Output page of the Propagation Loss Tool, giving the user insight into the mechanics of the model deemed the most accurate propagation loss prediction tool.

Upon completion of the Propagation Loss Tool several sets of parameters were compiled to test and validate the best fit model function of the Propagation Loss Tool.

| Scenario #: | One | Two | Three | Four | Five | Six | Seven |
|---|---|---|---|---|---|---|---|
| Base Station Antenna Height: | 10 | 250 | 400 | 190 | 90 | Any | Any |
| Mobile Station Antenna Height: | 2 | 8 | 15 | 9 | 7 | Any | Any |
| Distance: | 3 | 90 | 30 | 19 | 8 | Any | Any |
| Frequency: | 1000 | 2500 | 200 | 800 | 1900 | Any | Any |
| Environment: | Urban | Urban | Urban | Urban | Urban | Open | Suburban |
| Expected Best Fitted Model: | Walfisch - Ikegami | Modified Hata | Urban Hata w/ Errors | Urban Hata | Extended Hata | Open Hata | Surburban Hata |

Table 1. Propagation Loss Test Scenarios

These data sets are shown in Table 1 along with the expected resultant best fit model. When evaluated with the flow chart of Figure 14 using the standards of the parameter table in Figure 3, the user can consistently achieve the same intuitive preferred tool result that is shown above in Table 1 as those obtained when using the Excel Propagation Loss Tool.

### 1. Scenario One – Walfisch-Ikegami Model

Scenario one (from Table 1) falls within the restrictive parameter windows of the Walfisch-Ikegami model, with a base station antenna height of 10 meters, a mobile station antenna height of 2 meters, transmission distance of 3 kilometers, and 1000 megahertz for the frequency. As expected, when the parameters of scenario one were entered into the Input page of the Propagation Loss Tool, the final section of the Output page shown in the Figure 15 results indicates that the Walfisch-Ikegami model is in fact the model of choice (which identifies the loss as 163.00 dB). In this scenario, all the models produced loss results that are more than twice that of the free space loss calculation of 69.41 dB. Note that all of the urban type model losses are within about 10 percent of each other, indicating that using any of the available urban models in this case would provide a decent loss prediction. From the loss calculations in Figure 15, it is easy to see that the free space, open area Hata, and suburban Hata models, however, both produce losses that are significantly less than the other models (i.e., under predict the loss identified by the urban models).

| Based on your parameters, the best model to use is the: | Walfisch - Ikegami Model |
|---|---|

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 148.93 dB | 139.29 dB | 120.83 dB | 152.57 dB | 144.93 dB | 69.41 dB | 163.00 dB |

Figure 15. Snapshot of Output Page for Scenario One

### 2. Scenario Two – Modified Hata Model

The parameters of scenario two consisting of a base station antenna height of 250 meters, a mobile station antenna height of 8 meters, transmission distance of 90 kilometers, and a frequency of 2500 megahertz, resulted in the expected recommendation of the Modified Hata model (which identifies the loss as 158.80 dB). One notable difference in this evaluation scenario, shown in Figure 16, is the Walfisch-Ikegami loss (which identifies the loss as 205.82 dB). Because the parameters of scenario two fall well outside the acceptable ranges for the Walfisch-Ikegami model resulting in a loss that has significantly deviated from the average of the other values.

| Based on your parameters, the best model to use is the: | Modified Hata Model |
|---|---|

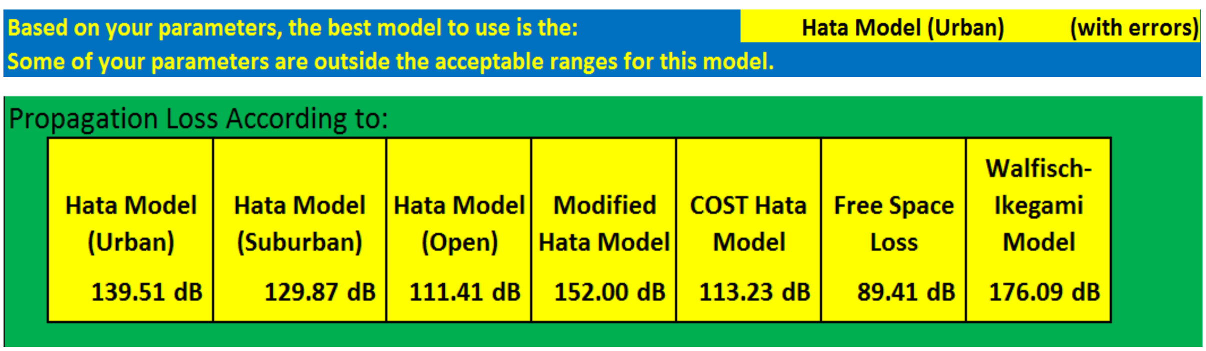
Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 161.92 dB | 152.28 dB | 133.82 dB | 158.80 dB | 149.41 dB | 98.96 dB | 205.82 dB |

Figure 16. Snapshot of Output Page for Scenario Two

### 3. Scenario Three – Urban Hata Model with Errors

Figure 17 shows the results of entering the parameters from assessment scenario three. With a base station antenna height of 400 meters, a mobile station antenna height of 15 meters, transmission distance of 30 kilometers, and 200 megahertz for the frequency, this scenario involves parameters that do not quite fall within the acceptable windows of the urban Hata model, but the resultant urban Hata model loss (which identifies the loss as 139.51 dB) usually occurs in the middle of the losses of the other models, and is therefore a good model for approximating the loss when the parameters do not meet the criteria of any of the other models.



Based on your parameters, the best model to use is the: Hata Model (Urban) (with errors)
Some of your parameters are outside the acceptable ranges for this model.

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 139.51 dB | 129.87 dB | 111.41 dB | 152.00 dB | 113.23 dB | 89.41 dB | 176.09 dB |

Figure 17. Snapshot of Output Page for Scenario Three

### 4. Scenario Four – Urban Hata Model

In Figure 18, the results of scenario four indicate that the urban Hata model (which identifies the loss as 144.19 dB) is the best choice. With a base station antenna height of 190 meters, a mobile station antenna height of 9 meters, transmission distance of 19 kilometers, and 800 megahertz for the frequency, the parameters all fit in the windows of accuracy. This scenario is a good example to

step back and show a general common sense type of validation. The calculated free space loss (which identifies the loss as 85.45 dB) is significantly less than all of the other values. It makes sense that this number would be less because the free space loss is simply accounting for the spreading of the signal as it propagates through open space. The open area Hata model loss (116.09 dB) is slightly more, indicating losses over open terrain, which are greater than just the spreading loss of the free space model. Again, this makes logical sense. Next in order is the loss of the COST Hata model (129.84). Common sense would tell a user that the suburban Hata model should be the next greatest loss. In this situation, it is difficult to tell if the COST (extended) Hata model is producing an accurate loss value. This model is composed of logarithmic functions based on higher frequencies than most of the other models. The fact that the frequency of this scenario falls below the acceptable COST Hata range indicates that the resultant loss would have a certain degree of inaccuracy, but because the focus of this particular model is on the higher frequency, the functions may produce losses that deviate from the norm by a greater degree. The suburban Hata model (134.55 dB) still takes its rightful place between the open area Hata (116.09 dB) and the urban Hata models (144.19 dB). With corrections accounted for that reduce the loss from the urban Hata model, it makes sense that the suburban model would produce a resultant loss greater than that of the open area and less than the urban models.

| Based on your parameters, the best model to use is the: | Hata Model (Urban) |
|---|---|

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 144.19 dB | 134.55 dB | 116.09 dB | 153.92 dB | 129.84 dB | 85.45 dB | 179.18 dB |

Figure 18. Snapshot of Output Page for Scenario Four

The urban Hata model is next. With all the parameters of this scenario satisfying the limits of the urban Hata model, this model is expected to produce the most accurate propagation loss value, and is identified to the user as the preferred result. The Modified Hata model produces the next highest loss prediction. Having been designed to carry predictions out over greater distances and frequencies with a known deviation from the actual loss values, this model was intended to compensate for the seemingly constant under estimated loss produced by the urban Hata model, which would lead one to believe that the resultant loss would always be slightly greater than that of the urban Hata model (validated by the approximately 10 dB higher result for scenario 4 in Figure 18). As discussed earlier, with such restrictive parameter limitations, the Walfisch-Ikegami model has only a small window of potentially accurate loss calculations before deviating significantly from the actual expected loss value and therefore should not be used. This is observed in scenario four as the Walfisch-Ikegami model tops out the calculated losses (which identifies the loss as 179.18 dB) more than 20 percent higher than any of the other models.

### 5. Scenario Five – COST Hata Model

The results of scenario five in Figure 19 show the COST (extended) Hata model as the best fit model (which identifies the loss as 142.96 dB). The base station antenna height is set at 90 meters, the mobile antenna at 7 meters, the transmission distance at 8 kilometers, and the frequency is 1900 megahertz. In this situation it is observed that a given scenario that falls within the parameter limits of the COST Hata model produces a predicted loss closer in line with that of the urban Hata model (140.71 dB), which should give the user an indication of the accuracy of the calculated figure.

**Based on your parameters, the best model to use is the:** **COST Hata Model**

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 140.71 dB | 131.07 dB | 112.61 dB | 149.88 dB | 142.96 dB | 77.93 dB | 166.74 dB |

Figure 19. Snapshot of Output Page for Scenario Five

### 6. Scenario Six – Open Area Hata Model

Figure 20 shows the results of scenario six. The logical sequence deriving the best suited model in this case is simply based on the environment type, but in comparison to the free space loss and the suburban Hata model, it makes sense that the open Hata model (which identifies the loss as 84.60 dB) is in fact the best model for this scenario.

| Based on your parameters, the best model to use is the: | Hata Model (Open) |
|---|---|

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 112.70 dB | 103.06 dB | 84.60 dB | 206.47 dB | 142.96 dB | 77.93 dB | 166.74 dB |

Figure 20. Snapshot of Output Page for Scenario Six

#### 7. Scenario Seven – Suburban Hata Model

Just like scenario six, the results of scenario seven in Figure 21 are based primarily on the environment type. It makes sense that the suburban value (which identifies the loss as 121.43 dB) falls between the open area (102.97) and urban Hata (131.07 dB) models, and that it is in fact the correct model to use for this situation.

| Based on your parameters, the best model to use is the: | Hata Model (Suburban) |
|---|---|

Propagation Loss According to:

| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
|---|---|---|---|---|---|---|
| 131.07 dB | 121.43 dB | 102.97 dB | 261.67 dB | 142.96 dB | 77.93 dB | 166.74 dB |

Figure 21. Snapshot of Output Page for Scenario Seven

## B. IMPACT OF VARYING PARAMETERS

Two of the main utilities of the developed Propagation Loss Tool is to show the significance each setup parameter plays in the amount of propagation loss experienced in a

certain environment and to educate the user on the sensitivity of modifying any of the adjustable parameters. In the evaluation that follows, independence of parameters is assumed (i.e., the variation of a specific parameter is assumed to not affect any of the other model parameter values). Although only one parameter was tested at a time with the others held constant as controls, each test was performed several times so that the other control parameters could be adjusted to fit within the specified limits of each model and enhance confidence in the results.

### 1. Base Station Antenna Height

Table 2 shows that most of the models had about a ten percent decrease in the calculated loss value by raising the base station antenna height from the minimum to the maximum recommended height. Although the numbers cannot be verified without actual testing, the general trend is supported by a common sense validation. It makes sense that raising the antenna in a fixed environment would decrease the losses encountered in the propagation path. By raising the base station antenna, in most cases over 100 meters, the transmission path becomes less obstructed by buildings and other structures, therefore reducing the loss. This information is valuable due to the fact that the base station antenna height and position is one of the controllable factors involved in establishing a communications system configuration.

| | Base Station Antenna Height | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | 4 m | 50 m | 170 dB | 153 dB | 10.0% |
| Modified Hata | 30 m | 300 m | 170 dB | 157 dB | 7.6% |
| COST Hata | 30 m | 200 m | 146 dB | 130 dB | 11.0% |
| Urban Hata | 30 m | 200 m | 154 dB | 137 dB | 11.0% |
| Suburban Hata | 30 m | 200 m | 135 dB | 118 dB | 12.6% |
| Open Area Hata | 30 m | 200 m | 98 dB | 82 dB | 16.3% |

*For each model, the control parameters were adjusted to the middle of each of the acceptable ranges.

Table 2. Impact of Varying Base Station Antenna Height

### 2. Mobile Station Antenna Height

Adjusting the mobile station antenna height had a minimal effect on the calculated loss for most models. This result is due to the fact that the highest allowable limit for the mobile station antenna is 10 meters, which in most urban environments is still well below the average building height and the 30 meter base station antenna height minimum for most models. As shown in Table 3, the most significant change occurred with the open area Hata model, which is expected. The primary influential factors in the open area Hata model are transmission distance and frequency. Raising either one of the antennas would result in a more direct, unobstructed transmission path (which produced an 11 dB smaller loss and a corresponding 11 percent change as shown).

| | Mobile Station Antenna | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | 1 dB | 3 dB | 155 dB | 153 dB | 1.3% |
| Modified Hata | 1 dB | 10 dB | 162 dB | 162 dB | 0.0% |
| COST Hata | 1 dB | 10 dB | 143 dB | 133 dB | 7.0% |
| Urban Hata | 1 dB | 10 dB | 151 dB | 140 dB | 7.3% |
| Suburban Hata | 1 dB | 10 dB | 131 dB | 121 dB | 7.6% |
| Open Area Hata | 1 dB | 10 dB | 95 dB | 84 dB | 11.6% |

*For each model, the control parameters were adjusted to the middle of each of the acceptable ranges.

Table 3. Impact of Varying Mobile Station Antenna Height

### 3. Transmission Distance

Varying the transmission distance had the greatest impact on the predicted propagation losses. Transmission distance is known to have a distance-squared effect on receive power so this finding confirms the expected strong dependencies on the distance between transmit and receive antennas. The major increase in the Walfisch-Ikegami model loss is due to the fact that the minimum transmission distance is only 0.02 kilometers, leaving little room for structural interference compared to the maximum distance of 5 kilometers. This variation is helpful in understanding the significance of transmission distance in the loss calculation, but applies to a parameter that would be difficult to change. One way a user may benefit from this test is to better understand the requirements for relay antennas in long distance transmission scenarios.

| | Transmission Distance | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | 0.02 dB | 5 dB | 71 dB | 162 dB | 128.2% |
| Modified Hata | 1 dB | 100 dB | 118 dB | 160 dB | 35.6% |
| COST Hata | 1 dB | 20 dB | 115 dB | 147 dB | 27.8% |
| Urban Hata | 1 dB | 20 dB | 112 dB | 154 dB | 37.5% |
| Suburban Hata | 1 dB | 20 dB | 94 dB | 134 dB | 42.6% |
| Open Area Hata | 1 dB | 20 dB | 57 dB | 98 dB | 71.9% |

*For each model, the control parameters were adjusted to the middle of each of the acceptable ranges.

Table 4. Impact of Varying Transmission Distance

### 4. Transmission Frequency

Altering the transmission frequency across the spectrum of acceptable parameters had little to no affect on the calculated losses of each model. The frequency is a factor in almost every equation in every model, but it is usually applied in a logarithmic scale so the difference between log(150) and log(1500) is only 1, therefore, not a significant contributor. In most of the models, the loss that occurs due to the physical parameters will occur regardless of the transmission frequency. Table 5 and most of the frequency range plots shown for the model output page show that the calculated loss remains fairly constant regardless of the frequency. With concerns of increased losses associated with the higher frequencies of modern communication systems, this is a significant find.

| | Transmission Frequency | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | 800 dB | 2000 dB | 154 dB | 154 dB | 0.0% |
| Modified Hata | 100 dB | 3000 dB | 162 dB | 162 dB | 0.0% |
| COST Hata | 1500 dB | 2000 dB | 137 dB | 143 dB | 4.4% |
| Urban Hata | 150 dB | 1500 dB | 144 dB | 144 dB | 0.0% |
| Suburban Hata | 150 dB | 1500 dB | 125 dB | 125 dB | 0.0% |
| Open Area Hata | 150 dB | 1500 dB | 89 dB | 89 dB | 0.0% |

*For each model, the control parameters were adjusted to the middle of each of the acceptable ranges.

Table 5. Impact of Varying Transmission Frequency

### 5. City Size

As shown in Table 6, altering the city size has a minimal impact on most models. The Walfisch-Ikegami model and the Modified Hata only use the size of the city to determine minor adjustments in correction factors, where as the city size based correction in the other models plays a more significant role. Based on the physical conditions of the open and suburban areas, city size does not seem like it should play a role in determining those losses, but both the open area Hata and suburban Hata involve equations that reduce the calculated loss from the urban Hata model, which does require an inputted city size to function correctly. The changes are small, but they do exist.

| | City Size | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | Small | Large | 154 dB | 154 dB | 0.0% |
| Modified Hata | Small | Large | 149 dB | 149 dB | 0.0% |
| COST Hata | Small | Large | 143 dB | 136 dB | 4.9% |
| Urban Hata | Small | Large | 145 dB | 140 dB | 3.4% |
| Suburban Hata | Small | Large | 131 dB | 135 dB | 3.1% |
| Open Area Hata | Small | Large | 112 dB | 117 dB | 4.5% |

*For each model, the control parameters were adjusted to the middle of each of the acceptable ranges.

Table 6. Impact of Varying City Size

## 6. Percentage of Buildings

The percentage of buildings factor only applies to the modified Hata model. The parameter limitations are 3 percent to 50 percent, and the change in the calculated loss at those two extremes is very significant, as shown in Table 7. If the actual percentage of building is unknown, an estimate within 10 percent of the actual value would produce a calculated loss less than 2 percent off of the correct loss.

| | Percentage of Buildings | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | N/A | N/A | N/A | N/A | N/A |
| Modified Hata | 3 % | 50 % | 127 dB | 158 dB | 24.4% |
| COST Hata | N/A | N/A | N/A | N/A | N/A |
| Urban Hata | N/A | N/A | N/A | N/A | N/A |
| Suburban Hata | N/A | N/A | N/A | N/A | N/A |
| Open Area Hata | N/A | N/A | N/A | N/A | N/A |

Table 7. Impact of Varying Percentage of Buildings

### 7. Building Separation and Street Width

The building separation is a parameter only required if the street width is unknown. Of the two, the street width is the only one actually applied in an equation, and only in the Walfisch-Ikegami model. Varying the street width between the minimum 10 meters and the maximum 25, produces only a slight change in the calculated loss as shown in Table 8. Visualizing the two different scenarios leads one to believe that the wider street would in fact result in a smaller loss because there would be more open air for the signal to travel through without interference. This intuition is confirmed by the W-I model results shown in Table 8 where the loss as a function of width decreased by 9 dB over the range considered.

| | Building Sep/Street Width | | Associated Loss | | Change in Loss |
|---|---|---|---|---|---|
| | Min | Max | Min | Max | |
| Walfisch-Ikegami | 20/10 m | 50/25 m | 165 dB | 156 dB | 5.5% |
| Modified Hata | N/A | N/A | N/A | N/A | N/A |
| COST Hata | N/A | N/A | N/A | N/A | N/A |
| Urban Hata | N/A | N/A | N/A | N/A | N/A |
| Suburban Hata | N/A | N/A | N/A | N/A | N/A |
| Open Area Hata | N/A | N/A | N/A | N/A | N/A |

Table 8. Impact of Varying Building Separation and Street Width

## C. VALIDATION

The biggest problem associated with all of the empirical propagation loss models used within this study is the lack of an ability to validate the data and model calculations. In order to truly know if the calculated

propagation losses are accurate, field transmission tests would be required in the actual environment of the input parameters. It would be almost impossible to experiment with variable parameters and conditions with enough coverage to extend the data to a general urban propagation model. Any actual data that has been collected in this field is city specific and could not be directly applied to any other city or environment. This is why there are only a handful of actual published sets of urban propagation data and why almost all of the developed propagation models are based on one of these few data sets. All of the models in this study are, in some way, based on the Hata model which was derived from Okumura’s propagation data gathered back in the 1960s. Even if an urban environment test bed were available, the vast variety of physical conditions that exist in a city would make it difficult to derive the exact parameters to enter into the models.

Without the ability to field test the accuracy of the predicted propagation losses, an effort will be made to verify that the results produced by the Propagation Loss Tool are calculated correctly. In order to accomplish this type of validation, parameter sets evaluated using the Propagation Loss Tool will also be entered into a variety of other propagation loss calculators, or compared to published examples, to test a few of the propagation loss models.

### 1. Validation of the Various Hata Models

The first validation test was done using a propagation loss calculator found online at Circuit Design

Incorporated.[48] This particular calculator is designed specifically for the Hata Model. The base station antenna height was set at 100 meters, the mobile station antenna at seven meters, the distance used was six kilometers, and the frequency was 1000 megahertz. All of these parameters fall within the acceptable parameter ranges of the urban Hata model. The results using the Propagation Loss Tool from this study are shown in Figure 22. The results from the online calculator are shown in Figure 23, only addressing the urban, suburban, and open area Hata models. Using the two different tools, all three models are within 5 dB of each other. At a distance of six kilometers the online calculator produced losses of 138 dB for the urban Hata model, 122 for the suburban Hata model, and 103 for the open Hata mode, compared to an urban loss of 135.83 dB, suburban loss of 126.19 dB, and an open area Hata loss of 107.73 for the Microsoft Excel Propagation Loss tool. Other tests were conducted comparing these two tools and varying the parameters, and all had similar results with only about a 5 dB difference between any of the corresponding outputs. There are some slight differences in the results of the two tools, such as the intersecting value of the open area Hata model and the free space loss, but all differences are still within a deviation of only a few decibels.

[48] "Okumura - Hata Curve," n.d., <http://www.cdt21.com/resources/siryo4_01.asp>(27 Aug 2009).

| Propagation Loss According to: | | | | | | |
|---|---|---|---|---|---|---|
| Hata Model (Urban) | Hata Model (Suburban) | Hata Model (Open) | Modified Hata Model | COST Hata Model | Free Space Loss | Walfisch-Ikegami Model |
| 135.83 dB | 126.19 dB | 107.73 dB | 145.22 dB | 138.08 dB | 106.06 dB | 161.99 dB |

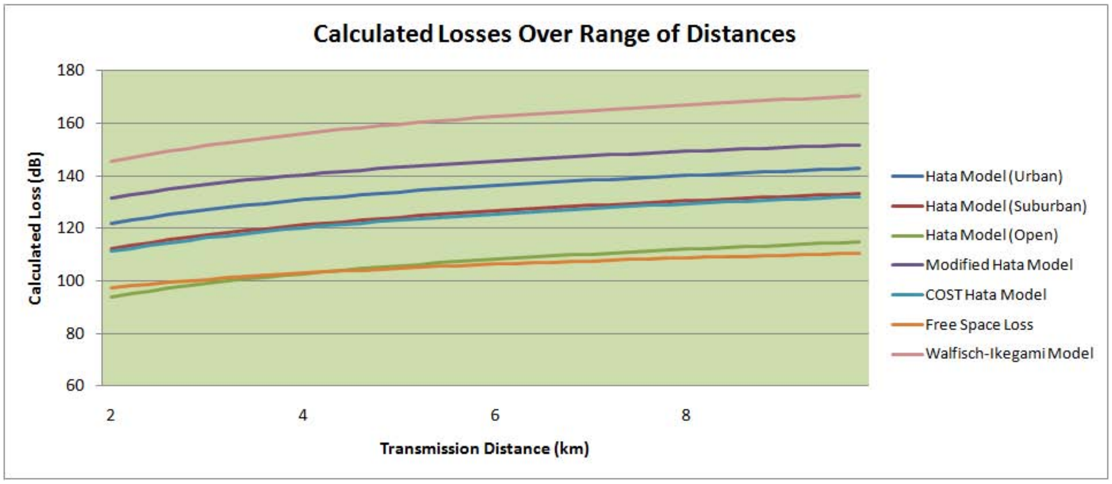



Figure 22. Propagation Loss Tool Validation Results

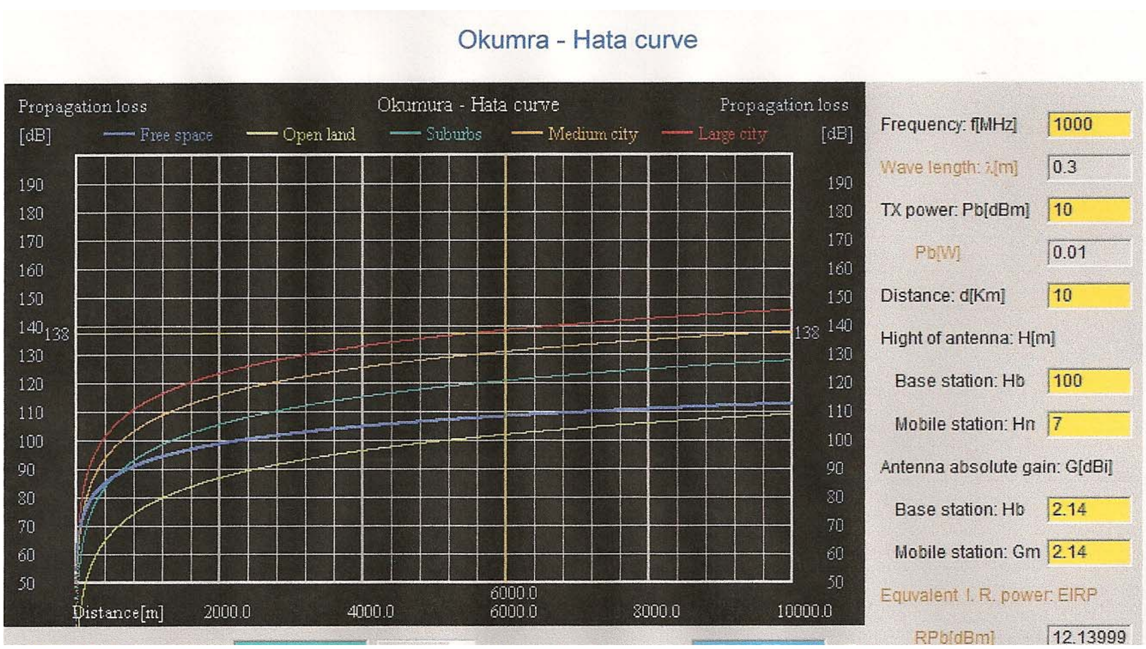



Figure 23. Online Calculator Validation Results[49]

49 "Okumura - Hata Curve," n.d., <http://www.cdt21.com/resources/siryo4_01.asp>(27 Aug 2009).

### 2. Validation of the Walfisch-Ikegami Model

The Walfisch-Ikegami portion of the Propagation Loss Tool was tested against an Australian example that provided results for both the Walfisch-Ikegami line-of-sight and non-line-of-sight calculations, as well as the free space loss.[50] Figure 24 shows the results of this study while Figure 25 displays the output of the Australian example. Although the output page of the Propagation Loss Tool does not display the line-of-sight values, they are calculated on a separate page within the spreadsheet for use when the user selects the line-of-sight option on the input page. At a distance of 0.253 kilometers, the Australian model produced a Walfisch-Ikegami non-line-of-sight loss of 126.14 dB, a line-of-sight loss of 85.72 dB, and a free space loss of 79.12 dB. The Propagation Loss tool resulted in a Walfisch-Ikegami NLOS loss of 125.21, LOS loss of 85.18 dB, and a free space loss of 78.56 dB. Despite the fact that this model is one of the more complex models, the results of both tools were within one decibel of each other for all three values tested. It may be the complex restrictive nature of this model that does not allow room for deviation, but the results of this test are a good indication that the Walfisch-Ikegami portion of the Propagation Loss Tool is in fact producing the correct results.

[50] "Walfisch-Ikegami loss model for Cellular System Planning," n.d., <http://members.iinet.net.au/~tonyart/Applets/Walfisch/SmallCell.html> (27 Aug 2009).

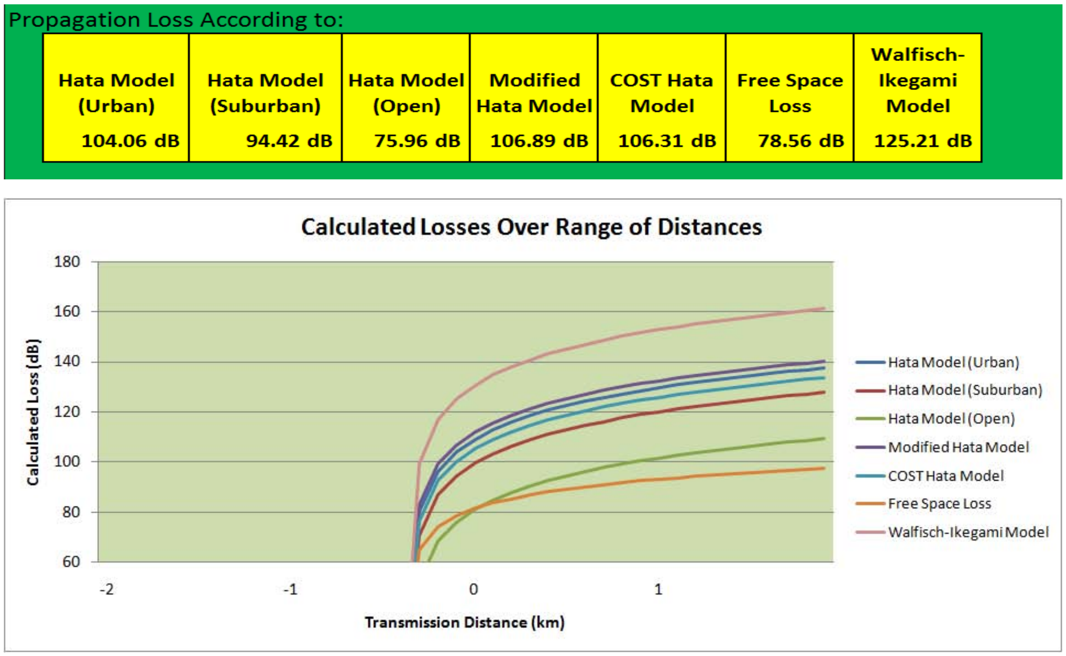



Figure 24. Walfisch-Ikegami Model Validation Results

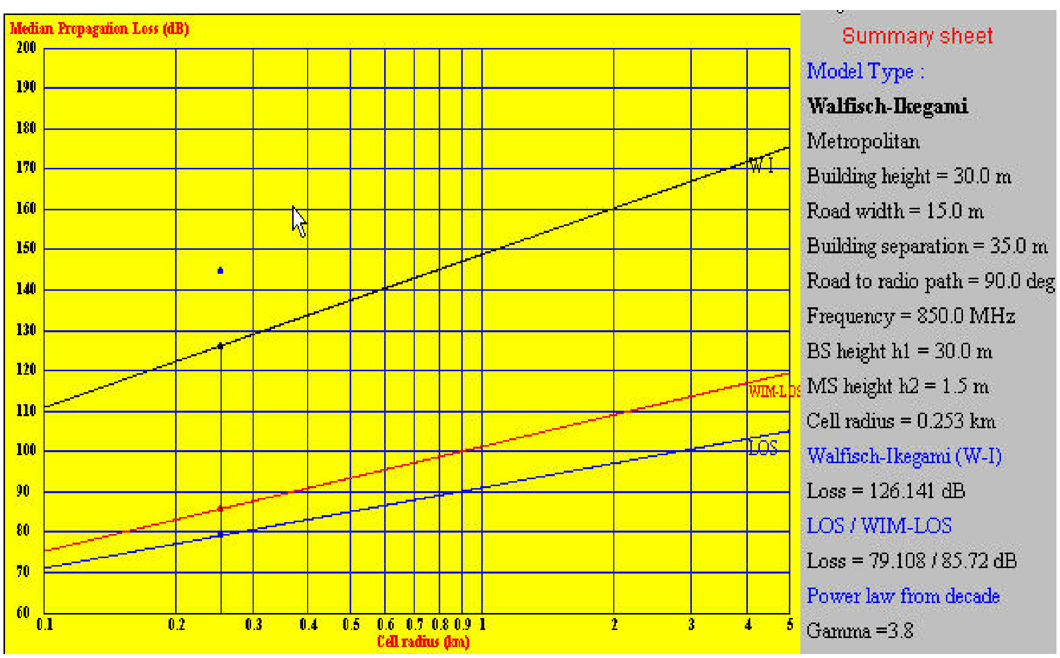



Figure 25. Australian Example Validation Results[51]

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51 "Walfisch-Ikegami loss model for Cellular System Planning," n.d., <http://members.iinet.net.au/~tonyart/Applets/Walfisch/SmallCell.html> (27 Aug 2009).

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# V. CONCLUSION

## A. SUMMARY

Propagation path loss is a significant concern when designing or attempting to improve wireless networks. When planning such a system, it is crucial that the communications engineer fully understand the potential losses that exist because these losses will affect the required transmission power, receiver sensitivity, equipment performance and placement of that equipment.[52] Predicting these losses ahead of time could save a great deal of time and money when setting up a cellular type network in an urban environment. Having a general idea of the power and equipment required in a friendly environment can be very beneficial but can also be verified with actual transmission tests before the system is hard wired and required for use. Operators in hostile environments are not afforded the luxury of having access to the environment ahead of time for test or even knowing the exact parameters of the environment that they will be operating in, which makes the estimation of radio wave propagation loss based on minimal input parameters essential to successful military communication operations.

This study did not derive any new or improved information in the area of propagation loss models, but it did develop a tool to help educate the user and simplify the propagation loss prediction process using existing models.

[52] Ian Poole, “Radio Signal Path Loss,” n.d., <http://www.fas.org/spp/military/docops/afwa/U2.htm> (23 Aug 2009).

Many sources in the literature review suggest that the urban Hata model is the most widely accepted propagation loss prediction model. The results of this thesis show that determination of the most accurate model is scenario dependent. That being said, throughout the investigation, the appeal of the urban Hata model became apparent. With only a few basic input parameters and no real required knowledge of the physical conditions of the transmission environment, the urban Hata model consistently produced results within 5 to 10 percent of the known most accurate model under a variety of conditions. The Propagation Loss Tool built as part of this study enables a user to not only calculate the expected propagation loss in any given environment, but also to adjust parameters and gain a better understanding of the impact of the physical conditions, positions of equipment, and transmission factors. As might be expected, tests showed that the greatest influence on propagation loss was the transmission distance. Whether the radio wave propagates over an open field or through a dense city, the longer the path through that particular environment, the greater the propagation loss experienced. If the operational requirement is to transmit from one point to another, knowing that the loss is less at a shorter distance may not seem beneficial, but it could help in determining the potential need and placement of relay antennas. Of the parameters that could potentially be adjusted by an operator or communications engineer, the height of the base station antenna affected the loss values the most because of the potential for an unobstructed line-of-sight link as the base station height is increased.

Another approach to extracting data from the output of this study would be to take the most conservative approach and account for the greatest loss of all the calculated values based on the given scenario. This could potentially result in a situation in which resources and funds are wasted attempting to over compensate for a loss that is not occurring to the degree perceived, but it would be better than under estimating the loss. This method could also be refined with an extra step analyzing the highest loss value. By comparing the input parameters to the limitations of the model that produces the greatest loss, the user could determine if that particular model is expected to produce accurate results. If the parameters of the model predicting the greatest loss are within or close to the published limitations, then it is feasible to actually expect losses as high as that prediction, and worthwhile to use the highest value, despite the fact that another model might be recommended as the best choice. If, however, there are indications that the model producing that highest loss value is inaccurate, and that value is significantly larger than the best fitted model and the others, then the user is more than likely better off ignoring that high value.

## B. PROBLEMS

The greatest problem associated with propagation loss models is the inability to validate the results against actual data. Basic validations could be conducted using computer modeling, but to use an actual urban environment test bed would be difficult. The problem that arises in the urban environment is the impossibility that exists of knowing or predicting all of the factors involved that

influence the transmission of radio waves to include the size, shape, spacing, and composition of all the buildings in the transmission path. Even though many of the calculations are based on average values, without knowing these parameters, a certain degree of inaccuracy will be unavoidable. Despite the potentially accurate calculations based on approximations and generalizations, one flaw that exists with several of the models is the qualitative nature of some of the inputs such as city size. With no real mathematical definition of each category, these qualitative parameters are left to the discretion of the user. Although the impact studies of this thesis showed that the change in calculated loss across the spectrum of city sizes was small, selecting the wrong city size does increase the inaccuracy.

## C. FUTURE WORK

If it is to actually be used as an operational tool, the Microsoft Excel Propagation Loss Tool developed in this project needs to be refined. It provides a general comparison of a few of the urban propagation loss models, but there are a few bugs that have yet to be worked out. When combinations of input parameters are entered that reach beyond the extreme ends of the acceptable parameters range for certain models, erroneous output is displayed, providing the user with an incorrect estimate of the urban propagation loss. Further effort needs to be put into eliminating these false values or at least recognizing them as unacceptable and informing the user that the given conditions are producing invalid estimates.

Any study involving radio wave propagation loss in the urban environment can always use more data. Because the

models are only derived from curves based on a few samplings over 40 years ago, there is really no way to accurately validate the application of the models to various types of environments.

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# APPENDIX A. URBAN PROPAGATION LOSS TOOL

## INPUT

1) Open the file: Propagation Loss Tool.xls

2) In the bottom left corner of the spreadsheet, select the "Input" worksheet tab.

3) Select the first block in the yellow column and enter the height of the base station antenna in meters. Press Enter.

4) Enter the height of the mobile station antenna in meters. Press Enter.

5) Enter the distance between the base station and the mobile station in kilometers. Press Enter.

6) Enter the transmission frequency in Megahertz. Press Enter.

7) Select the type of environment from the drop down list: Open, Suburban, or Urban. Press Enter.

8) If you've selected an urban environment, select the size of the city from the drop down list: Small, Medium, or Large. Press Enter.

9) If known, enter the percentage of the area of buildings vs. the entire area of the city. If that number is unknown, enter a default value of 30 percent. Press Enter.

10) Enter the average height of the buildings in the area in meters. Press Enter.

11) Enter the average distance between buildings. Press Enter.

12) Enter the width of streets in the area. If unknown, divide the distance between buildings by two. Press Enter.

13) Enter the base station antenna gain in dB. Press Enter.

14) Enter the mobile station antenna gain in dB. Press Enter.

15) From the drop down list, select whether the transmission pat is line-of-sight or obstructed. Press Enter.

**OUTPUT**

1) In the bottom left corner of the spreadsheet, select the “Output” worksheet tab.

2) The results are displayed on this page.

3) The yellow blocks at the top of the page display the exact losses calculated according to each of the propagation loss models based on the parameters entered on the previous page.

4) The graph on the left extends the losses out over a range of frequencies to display the effect that altering the transmission frequency would have on the propagation loss. It also shows a visual display of the variation between the loss associated with each model and the free space loss.

5) The graph on the right extends the losses out over a range of distances to display the effect that altering the transmission distance would have on the propagation loss. It also shows a visual display of the variation between the loss associated with each model and the free space loss.

6) The yellow box below the graphs indicates the propagation model best suited for the parameters entered on the previous page.

7) The blue box at the bottom of the page displays the calculation details of the model which best fits the parameters entered on the previous page.

# APPENDIX B. CALCULATIONS

Below is a series of calculations required to achieve one data point on the graphs of the Output page of the Propagation Loss Tool developed using Microsoft Excel. Each data point used requires all of these calculations. The intent of this document is not to provide an understanding of the equations required in each model, but simply to demonstrate the complexity of each step involved in the process.

```
=IF(($AD7+$AE7)<0,$AC7,($AC7+$AD7+$AE7))

=Calculations!$Q$40+Calculations!$Q$30+Calculations!$Q$31*LO
G10(Calculations!$G$10)+$AA7*LOG10($D7)-
9*LOG10(Calculations!$G$16)

=-16.9-
10*LOG10(Calculations!$G$17)+10*LOG10($D7)+20*LOG10(Calculat
ions!$Q$26)+Calculations!$Q$38

=32.45+20*LOG10(Calculations!$G$10)+20*LOG10($D7)

=42.64+26*LOG10(Calculations!$G$10)+20*LOG10($D7)

=IF(Calculations!$G$12="Large",    (-4+1.5*(($D7/925)-1)),(-
4+0.7*(($D7/925)-1)))

=IF(Calculations!$G$13="Open",4.78*(LOG10($D7)^2)-
18.33*LOG10($D7)+40.94,IF(Calculations!$G$13="Suburban",2*(L
OG10($D7/28)^2)+5.4,0))

=IF(Calculations!$G$12="Large",3,0)

=25*LOG10(Calculations!$G$14*100)-30

=((1-
IF(Calculations!$G$12="Small",0,IF(Calculations!$G$13="Mediu
m",0,1)))*$P7)+(IF(Calculations!$G$12="Small",0,IF(Calculati
ons!$G$13="Medium",0,1))*(($Q7*$S7)+($R7*$T7)))
```

```
=(1-
IF(Calculations!$G$13="Open",0,IF(Calculations!$G$13="Suburb
an",0.5,1)))*((1-
(2*IF(Calculations!$G$13="Open",0,IF(Calculations!$G$13="Sub
urban",0.5,1))))*$G7+(4*IF(Calculations!$G$13="Open",0,IF(Ca
lculations!$G$13="Suburban",0.5,1))*$F7))
=(27+($D7/230))*LOG10((17*(Calculations!$G$8+20))/((17*(Calc
ulations!$G$8+20))+(Calculations!$G$10^2)))+1.3-((ABS($D7-
55))/750)

=(($D7^4)/(($D7^4)+(300^4)))

=((300^4)/(($D7^4)+300^4))

=((3.2*((LOG10(11.75*Calculations!$G$9))^2))-4.97)

=((8.28*((LOG10(1.54*Calculations!$G$9))^2))-1.1)

=0.8+(((1.1*LOG10($D7))-0.7)*Calculations!$G$9)-
(1.56*LOG10($D7))

=IF(Calculations!$G$12="Large",IF(AND(150<=$D7,$D7<=200),((8
.28*((LOG10(1.54*Calculations!$G$9))^2))-
1.1),IF(AND(200<$D7,$D7<=1500),((3.2*((LOG10(11.75*Calculati
ons!$G$9))^2))-4.97),"Frequency Error")),"Using Small City
Data")

=IF(Calculations!$G$12="Small",0.8+(((1.1*LOG10($D7))-
0.7)*Calculations!$G$9)-
(1.56*LOG10($D7)),IF(Calculations!$G$12="Medium",0.8+(((1.1*
LOG10($D7))-0.7)*Calculations!$G$9)-(1.56*LOG10($D7)),"Using
Large City Data"))

=IF(Calculations!$G$20="LOS",$AB7,$AF7)

=46.33+(44.9-
6.55*(LOG10(Calculations!$G$8)))*LOG10(Calculations!$G$10)+3
3.9*(LOG10($D7))-IF(Calculations!$G$12="Large",$O7,$N7)-
13.82*(LOG10(Calculations!$G$8))+$Y7

=((-10*LOG10(Calculations!$G$18))-
(10*LOG10(Calculations!$G$19))+(20*LOG10($D7))+(20*LOG10(Cal
culations!$G$10))+21.98)
```

```
=46.3+(33.9*LOG10($D7))-(13.82*LOG10(Calculations!$G$8))-
$P7+((44.9-
(6.55*LOG10(Calculations!$G$8)))*LOG10(Calculations!$G$10))-
$Y7

=($E7+$V7+$W7+$U7+$X7)

=E7-(4.78*((LOG10($D7))^2))+(18.3*LOG10($D7))-40.94
=$E7-(2*(LOG10($D7/28)^2))-5.4

=69.55+(26.16*LOG10($D7))-(13.82*LOG10(Calculations!$G$8))-
IF(Calculations!$G$12="Small",$N$27,IF(Calculations!$G$12="M
edium",$N$27,$O$27))+(44.9-
(6.55*LOG10(Calculations!$G$8)))*LOG10(Calculations!$G$10)-
$Z7
```

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